

AD-A208 814

DTIC FILE COPY

1

ESL-TR-87-67

# SOIL-GAS AND GEOPHYSICAL TECHNIQUES FOR DETECTION OF SUBSURFACE ORGANIC CONTAMINATION

A.M. PITCHFORD, A.T. MAZZELLA, K.R. SCARBROUGH

ENVIRONMENTAL MONITORING SYSTEMS  
LABORATORY  
P.O. BOX 93478  
LAS VEGAS NV 89139-3479

JANUARY 1989

FINAL REPORT

MARCH 1985 — NOVEMBER 1987

SDTIC  
ELECTE  
JUN 12 1989  
Cb H

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED



# AFGSC

ENGINEERING & SERVICES LABORATORY  
AIR FORCE ENGINEERING & SERVICES CENTER  
TYNDALL AIR FORCE BASE, FLORIDA 32403

89 6 12 036

NOTICE

PLEASE DO NOT REQUEST COPIES OF THIS REPORT FROM  
HQ AFESC/RD (ENGINEERING AND SERVICES LABORATORY).

ADDITIONAL COPIES MAY BE PURCHASED FROM:

NATIONAL TECHNICAL INFORMATION SERVICE  
5285 PORT ROYAL ROAD  
SPRINGFIELD, VIRGINIA 22161

FEDERAL GOVERNMENT AGENCIES AND THEIR CONTRACTORS  
REGISTERED WITH DEFENSE TECHNICAL INFORMATION CENTER  
SHOULD DIRECT REQUESTS FOR COPIES OF THIS REPORT TO:

DEFENSE TECHNICAL INFORMATION CENTER  
CAMERON STATION  
ALEXANDRIA, VIRGINIA 22314

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

## REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

|   |   |  |                                     |
|---|---|--|-------------------------------------|
| 1a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED  |   | 1b. RESTRICTIVE MARKINGS   |                                     |
| 2a. SECURITY CLASSIFICATION AUTHORITY   |   | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release, distribution unlimited. |                                     |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE   |   | 5. MONITORING ORGANIZATION REPORT NUMBER(S)<br>ESL-TR-87-67                                    |                                     |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)   |   | 7a. NAME OF MONITORING ORGANIZATION<br>Air Force Engineering & Services Center                 |                                     |
| 6a. NAME OF PERFORMING ORGANIZATION<br>U.S. Environmental Protection Agency   | 6b. OFFICE SYMBOL<br>(If applicable)<br>EMSL-LV | 7b. ADDRESS (City, State, and ZIP Code)<br>HQ AFESC/RDWW<br>Tyndall AFB FL 32403-6001          |                                     |
| 6c. ADDRESS (City, State, and ZIP Code)<br>Environmental Monitoring Systems Laboratory<br>P.O. Box 93478<br>Las Vegas NV 89139-3479   |   | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>MIPR No. FY8952-85-10011 14707              |                                     |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION   | 8b. OFFICE SYMBOL<br>(If applicable)            | 10. SOURCE OF FUNDING NUMBERS  |                                     |
| 8c. ADDRESS (City, State, and ZIP Code)   |   | PROGRAM ELEMENT NO.<br>2054  | PROJECT NO.<br>30                   |
|   |   | TASK NO.<br>53   | WORK UNIT ACCESSION NO.             |
| 11. TITLE (Include Security Classification)<br>Soil-Gas and Geophysical Techniques for Detection of Subsurface Organic Contamination  |   |  |                                     |
| 12. PERSONAL AUTHOR(S)<br>Ann M. Pitchford, Aldo T. Mazzella, and Ken R. Scarbrough   |   |  |                                     |
| 13a. TYPE OF REPORT<br>Final  | 13b. TIME COVERED<br>FROM 050304 TO 871105      | 14. DATE OF REPORT (Year, Month, Day)<br>January 1989  | 15. PAGE COUNT                      |
| 16. SUPPLEMENTARY NOTATION<br>Availability of this is specified on reverse of front cover.  |   |  |                                     |
| 17. COSATI CODES  |   | 18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)              |                                     |
| FIELD   | GROUP   | SUB-GROUP  |                                     |
|   |   |  |                                     |
|   |   |  |                                     |
| 19. ABSTRACT (Continue on reverse if necessary and identify by block number)<br>The purpose of this effort was to provide guidance to Air Force Installation Restoration Program managers on the use of geophysical and soil gas reconnaissance techniques for detecting organic contaminants in the subsurface. Electromagnetic induction and direct current resistivity surface geophysical techniques and two soil gas monitoring techniques were tested at four Air Force bases. These techniques provide timely preliminary site information to assist in proper placement of monitoring wells. This will reduce the duration of site investigations and expense due to hit-and-miss placement of monitoring wells. In addition, a panel of expert hydrogeologists, chemists, and geophysicists provided guidance on the use of these reconnaissance techniques. Active soil gas monitoring, where a gas sample is extracted from the soil for analysis, was the most successful method for detecting volatile organic compounds. Passive soil gas monitoring,<br>(Continued on Reverse) |   |  |                                     |
| 20. DISTRIBUTION/AVAILABILITY OF ABSTRACT<br><input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS  |   | 21. ABSTRACT SECURITY CLASSIFICATION   |                                     |
| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>Bruce J. Nielser   |   | 22b. TELEPHONE (Include Area Code)<br>904-283-2942   | 22c. OFFICE SYMBOL<br>HQ AFESC/RDWW |

DD Form 1473, JUN 86

Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

Block 19 Continuation

Where vapors are collected on a sorbent trap, often failed to indicate organics when they were present. More research in this area is required with respect to passive soil gas monitor placement and duration of exposure. Generally, geophysical methods were successful for detecting hydrogeological features, buried metal objects, and conductive plumes, but were unsuccessful for detecting organic contaminants. Keywords:

Soil Contamination Groundwater Pollution. (AW) \*

# PREFACE

This report was prepared by the US Environmental Protection Agency, Environmental Monitoring Systems Laboratory-Las Vegas, P.O. Box 93478, Las Vegas, Nevada 89193-3478, under Interagency Agreement RW57931282-01-1, for the Air Force Engineering and Services Center, Engineering and Services Laboratory (HQ AFESC/RDVW), Tyndall Air Force Base, Florida 32403-6001.

Research documented in this report was performed between April 1985 and July 1987. HQ AFESC/RDVW project officers were Captain Edward Heyse and Mr Bruce Nielsen.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

*Bruce Nielsen*

BRUCE J. NIELSEN  
Project Officer

*Thomas J. Walker*

THOMAS J. WALKER, Lt Col, USAF, BSC  
Chief, Environics Division

*F. Thomas Lubczynski*

F. THOMAS LUBCZYNSKI, Maj, USAF, BSC  
Chief, Environmental Engineering Branch

*Lawrence D. Hokanson*

LAWRENCE D. HOKANSON, Colonel, USAF  
Director, Engineering and Services  
Laboratory



|                    |                                     |
|--------------------|-------------------------------------|
| Accession For      |                                     |
| NTIS GRA&I         | <input checked="" type="checkbox"/> |
| DTIC TAB           | <input type="checkbox"/>            |
| Unannounced        | <input type="checkbox"/>            |
| Justification      |                                     |
| By _____           |                                     |
| Distribution/      |                                     |
| Availability Codes |                                     |
| Dist               | Avail and/or<br>Special             |
| A-1                |                                     |

# TABLE OF CONTENTS

| Section | Title   | Page |
|---------|---|------|
| I       | INTRODUCTION.....                                   | 1    |
|         | A. OBJECTIVES.....                                  | 1    |
|         | B. BACKGROUND.....                                  | 1    |
|         | C. SCOPE.....                                       | 1    |
| II      | APPROACH.....                                       | 3    |
|         | A. OVERVIEW.....                                    | 3    |
|         | B. PANEL OF EXPERTS.....                            | 3    |
|         | C. SELECTION OF STUDY AREAS FOR INVESTIGATION.....  | 4    |
| III     | METHODS.....  | 6    |
|         | A. INTRODUCTION.....                                | 6    |
|         | B. SUMMARY OF METHODS USED AT AIR FORCE BASES.....  | 6    |
|         | C. SOIL GAS TECHNIQUES.....                         | 7    |
|         | 1. Theory.....                                      | 7    |
|         | 2. Overview of Techniques.....                      | 10   |
|         | a. Active Soil Gas Sampling.....                    | 11   |
|         | b. Passive Soil Gas Sampling.....                   | 14   |
|         | D. GEOPHYSICAL TECHNIQUES.....                      | 16   |
|         | 1. Introduction.....                                | 16   |
|         | 2. Electromagnetic Induction.....                   | 17   |
|         | 3. Direct Current and Complex Resistivity.....      | 17   |
|         | 4. Ground-Penetrating Radar.....                    | 21   |
|         | 5. Seismic Techniques.....                          | 21   |
|         | 6. Magnetometry.....                                | 24   |
|         | 7. Detection of Organic Contamination.....          | 24   |
| IV      | FIELD INVESTIGATIONS.....                           | 27   |
|         | A. INTRODUCTION.....                                | 27   |
|         | B. DISCUSSION OF SOIL GAS RESULTS.....              | 27   |
|         | 1. Active Soil Gas Sampling.....                    | 27   |
|         | 2. Passive Soil Gas Sampling.....                   | 32   |
|         | C. GEOPHYSICAL RESULTS.....                         | 33   |
| V       | GENERAL CONSIDERATIONS FOR SITE INVESTIGATIONS..... | 34   |
|         | A. INTRODUCTION.....                                | 34   |
|         | B. CATEGORIES OF ORGANIC COMPOUNDS.....             | 34   |
|         | C. CONCEPTUALIZING THE PROBLEM.....                 | 36   |

# TABLE OF CONTENTS (CONTINUED)

| Section | Title  | Page |
|---------|--|------|
| D.      | CONTAMINANT SOURCE SIZE.....   | 40   |
| E.      | COMPONENTS OF SITE INVESTIGATIONS.....   | 40   |
| F.      | PRELIMINARY INFORMATION.....   | 42   |
|         | 1. Hydrogeology.....   | 42   |
|         | 2. Soil, Surficial Geology, and Bedrock.....   | 43   |
|         | 3. Site Layout.....  | 43   |
|         | 4. Contaminant Source Information.....   | 44   |
|         | 5. Status of Early Knowledge.....  | 44   |
|         | 6. The Zone of Relevance.....  | 44   |
| G.      | GEOLOGICAL TECHNIQUES AND ISSUES.....  | 45   |
| H.      | HYDROLOGICAL TECHNIQUES AND ISSUES.....  | 46   |
| I.      | GEOCHEMICAL TECHNIQUES AND ISSUES.....   | 47   |
| J.      | ISOTOPIC TECHNIQUES AND ISSUES.....  | 48   |
| K.      | LITERATURE REVIEW.....   | 48   |
|         | 1. Fuel Leak Over Unconsolidated Sand and Gravel<br>Aquifer.....   | 49   |
|         | 2. Solvent Leak Over Sand and Gravel Aquifer.....  | 49   |
|         | 3. Landfill Over Unconsolidated Sand and Gravel Aquifer.....   | 52   |
|         | 4. Sewage Leach Field Over Unconsolidated Sand and<br>Gravel Aquifer.....  | 52   |
|         | 5. Leak Over Deep Aquifer.....   | 52   |
|         | 6. Fuel and Solvent Leak Over Two Interconnected<br>Aquifers.....  | 56   |
|         | 7. Fuel Leak Over Crystalline Fractured Rock.....  | 56   |
|         | 8. Fuel Leak Over Thick, Fissured Clay.....  | 56   |
|         | 9. Fuel Leak Over Karst Terrain.....   | 60   |
| VI      | PLANNING A SOIL GAS INVESTIGATION.....   | 62   |
| A.      | INTRODUCTION.....  | 62   |
| B.      | GENERAL CONSIDERATIONS.....  | 62   |
|         | 1. Physical Properties of Contaminants.....  | 63   |
|         | 2. Physical States and Depths of Contaminants.....   | 63   |
|         | 3. Hydrologic and Geologic Issues.....   | 66   |
|         | 4. Interference from Surface or Subsurface Sources.....  | 67   |
| C.      | COMPOUND-SPECIFIC INFORMATION.....   | 67   |
|         | 1. Halogenated Methanes, Ethanes, and Ethenes.....   | 67   |
|         | 2. Halogenated Propanes, Propenes, and Benzenes, and C <sub>9</sub><br>- C <sub>12</sub> Petroleum Hydrocarbons..... | 67   |
|         | 3. Halogenated Polycyclic Aromatics and Polycyclic Aro-<br>matic Hydrocarbons.....                                   | 68   |

TABLE OF CONTENTS  
(CONTINUED)

| Section    | Title   | Page |
|------------|---|------|
|            | 4. C <sub>1</sub> -C <sub>8</sub> Petroleum Hydrocarbons.....                 | 68   |
|            | 5. Low Molecular Weight Oxygenated Compounds.....                             | 68   |
|            | D. DEVELOPING AN INVESTIGATIVE PLAN.....                                      | 70   |
|            | E. INTERPRETATION OF RESULTS.....   | 71   |
|            | F. WHEN NOT TO USE SOIL GAS METHODS.....                                      | 72   |
| VII        | PLANNING A GEOPHYSICAL INVESTIGATION.....                                     | 73   |
|            | A. USES OF GEOPHYSICS.....  | 73   |
|            | B. CONSIDERATIONS IN DECIDING WHETHER TO USE GEOPHYSICS....                   | 76   |
|            | 1. General.....   | 76   |
|            | 2. Resistivity, EM, Ground-Penetrating Radar, and<br>Magnetic Techniques..... | 77   |
|            | 3. Ground-Penetrating Radar and Complex Resistivity....                       | 78   |
|            | 4. USGS Approach.....   | 79   |
|            | C. WHEN NOT TO USE GEOPHYSICAL METHODS.....                                   | 79   |
| VIII       | CONCLUSIONS.....  | 83   |
| IX         | RECOMMENDATIONS.....  | 84   |
|            | A. SOIL GAS TECHNIQUES.....   | 84   |
|            | B. GEOPHYSICAL TECHNIQUES.....  | 84   |
|            | C. INTEGRATED APPROACHES.....   | 85   |
|            | REFERENCES.....   | 86   |
| APPENDIXES |   |      |
| A          | HOLLOMAN AFB.....   | 93   |
|            | A. BACKGROUND.....  | 93   |
|            | B. GEOLOGY AND HYDROLOGY.....   | 93   |
|            | C. METHODS USED.....  | 93   |
|            | D. GROUND WATER RESULTS.....  | 98   |
|            | E. SOIL GAS RESULTS.....  | 102  |
|            | F. GEOPHYSICAL RESULTS.....   | 110  |
|            | G. SUMMARY.....   | 113  |
| B          | ROBINS AFB.....   | 117  |
|            | A. BACKGROUND.....  | 117  |



# TABLE OF CONTENTS (CONCLUDED)

| APPENDIXES | Title                                     | Page |
|------------|---|------|
| B.         | GEOLOGY AND HYDROLOGY.....                | 117  |
| C.         | METHODS USED.....                         | 117  |
| D.         | GROUND WATER RESULTS.....                 | 123  |
| E.         | SOIL GAS RESULTS.....                     | 124  |
|            | 1. Active Soil Gas Sampling Results.....  | 124  |
|            | 2. Passive Soil Gas Sampling Results..... | 132  |
| F.         | GEOPHYSICAL RESULTS.....                  | 137  |
| G.         | SUMMARY.....                              | 150  |
| C          | TINKER AFB.....                           | 151  |
| A.         | BACKGROUND.....                           | 151  |
| B.         | GEOLOGY AND HYDROLOGY.....                | 151  |
| C.         | METHODS USED.....                         | 151  |
| D.         | GROUND WATER RESULTS.....                 | 153  |
| E.         | SOIL GAS RESULTS.....                     | 158  |
|            | 1. Active Soil Gas Sampling.....          | 158  |
|            | 2. Passive Soil Gas Sampling.....         | 158  |
|            | 3. Comparisons.....                       | 169  |
| F.         | SUMMARY.....                              | 172  |

# LIST OF FIGURES

| Figure | Title   | Page |
|--------|---|------|
| 1      | Predictions of Volatile Organic Compound Concentration in the Subsurface.....                                 | 9    |
| 2      | Features of an Active Soil Gas Sampling System.....   | 12   |
| 3      | Passive Soil Gas Sampling Badge and Manifold.....   | 15   |
| 4      | Conceptual Diagram for an Electromagnetic (EM) Induction System.....  | 18   |
| 5      | Conceptual Diagram for a Direct Current Resistivity System.....   | 19   |
| 6      | Increased Electrode Spacing Samples Greater Depth and Volume of Earth.....                                    | 20   |
| 7      | Conceptual Diagram for a Ground-Penetrating Radar System.   | 22   |
| 8      | Conceptual Diagram of a Seismic Refraction System.....  | 23   |
| 9      | Conceptual Diagram of a Magnetometer.....   | 25   |
| 10     | Concentrations of Total Hydrocarbons in Soil Gas at JP-4 Spill Site, Robins AFB. Sampling Depth: 1 Meter..... | 30   |
| 11     | Concentrations of Total Hydrocarbons in Soil Gas at JP-4 Robins AFB. Sampling Depth: 2 Meters.....            | 31   |
| 12     | Vapor Pressure and Henry's Law Constant for Example Compounds in each Group.....                              | 35   |
| 13     | Fuel Leak Over Unconsolidated Sand and Gravel Aquifer....   | 50   |
| 14     | Solvent Leak Over Sand and Gravel Aquifer.....  | 51   |
| 15     | Landfill Over Unconsolidated Sand and Gravel Aquifer....  | 53   |
| 16     | Sewage Leach Field Over Unconsolidated Sand and Gravel Aquifer.....   | 54   |
| 17     | Leak Over Deep Aquifer.....   | 55   |
| 18     | Fuel and Solvent Leak Over Two Interconnected Aquifers...   | 57   |
| 19     | Fuel Leak Over Crystalline Fractured Rock.....  | 58   |
| 20     | Fuel Leak Over Thick Fissured Clay.....   | 59   |

LIST OF FIGURES  
(CONTINUED)

| Figure     | Title   | Page |
|------------|---|------|
| 21         | Fuel Leak Over Karst Terrain.....   | 61   |
| Appendixes |   |      |
| A-1        | BX Service Station, School, Hospital, Convenience Store and Residential Area at Holloman AFB.....                             | 94   |
| A-2        | Existing Wells and Soil Gas Measurement Locations at the BX Service Station, Holloman AFB.....                                | 95   |
| A-3        | Direct Current Resistivity and EM Measurement Locations at the BX Service Station, Holloman AFB.....                          | 96   |
| A-4        | Water Table Elevation Map for the Uppermost Aquifer, BX Service Station, Holloman AFB.....                                    | 99   |
| A-5        | Thickness of Floating Product at the BX Service Station, Holloman AFB.....  | 100  |
| A-6        | Xylene and Toluene in Ground Water and Floating Product at the BX Service Station, Holloman AFB.....                          | 101  |
| A-7        | Methane Soil Gas Concentrations at the BX Service Station, Holloman AFB.....  | 103  |
| A-8        | Total Non-Methane Hydrocarbon Soil Gas Concentrations at the BX Service Station, Holloman AFB.....                            | 104  |
| A-9        | Benzene Soil Gas Concentrations at the BX Service Station, Holloman AFB.....  | 105  |
| A-10       | o-Xylene Soil Gas Concentrations at the BX Service Station, Holloman AFB.....   | 106  |
| A-11       | Toluene Soil Gas Concentrations at the BX Service Station, Holloman AFB.....  | 107  |
| A-12       | Xylene and Toluene in Soil Gas, Ground Water, and Floating Product, BX Service Station, Holloman AFB.....                     | 108  |
| A-13       | Underground Utilities and the Distribution of Toluene in Soil Gas at the BX Service Station, Holloman AFB.....                | 111  |
| A-14       | Direct Current Resistivity Lines in Comparison to Total Hydrocarbons in Soil Gas at the BX Service Station, Holloman AFB..... | 112  |

LIST OF FIGURES  
(CONTINUED)

| Figure | Title   | Page |
|--------|---|------|
| A-15   | Comparison of dc Resistivity Pseudosections for Contaminated and Uncontaminated Areas at the BX Service Station at Holloman AFB.....  | 114  |
| A-16   | Apparent Resistivity Contour Map of EM-31 Vertical Dipole Data at the BX Service Station. Contour Interval is 5 Ohm Meters.....   | 115  |
| A-17   | Apparent Resistivity Contour Map of EM-31 Horizontal Dipole Data at the BX Service Station. Contour Interval is 5 Ohm Meters.....   | 116  |
| B-1    | JP-4 Spill Site, Fuel Farm, and Landfill No. 1 at Robins AFB.....   | 118  |
| B-2    | Direct Current Resistivity and EM Measurement Locations at JP-4 Spill Site, Robins AFB.....   | 121  |
| B-3    | Topographic Map of the JP-4 Spill Site Showing Relative Elevation Change (Meters) with Respect to the Base Station at Line A, Station 0 at JP-4 Spill Site, Robins AFB..... | 122  |
| B-4    | Concentrations of Total Hydrocarbons in Ground Water at the JP-4 Spill Site, Robins AFB.....  | 125  |
| B-5    | Concentrations of Benzene in Ground Water at the JP-4 Spill Site, Robins AFB.....   | 126  |
| B-6    | Concentrations of Toluene in Ground Water at the JP-4 Spill Site, Robins AFB.....   | 127  |
| B-7    | Concentrations of Total Hydrocarbons in Soil Gas at the JP-4 Spill Site, Robins AFB. Nominal 2 Meter (6 foot) Sampling Depth.....   | 128  |
| B-8    | Concentrations of Benzene in Soil Gas at the JP-4 Spill Site, Robins AFB. Nominal 2 Meter (6 foot) Sampling Depth.....  | 129  |
| B-9    | Concentrations of Toluene in Soil Gas at the JP-4 Spill Site, Robins AFB. Nominal 2 Meter (6 foot) Sampling Depth.....  | 130  |
| B-10   | Concentrations of Total Hydrocarbons in Soil Gas at the JP-4 Spill Site, Robins AFB. Nominal 1 Meter (3 foot) Sampling Depth.....   | 131  |

LIST OF FIGURES  
(CONTINUED)

| Figure | Title   | Page |
|--------|---|------|
| B-11   | Comparison of Soil Gas and Ground Water Data at the JP-4 Spill Site, Robins AFB.....  | 133  |
| B-12   | Location of Passive Samplers in Relation to Ground Water and Active Soil Gas Data at JP-4 Spill Site, Robins AFB..  | 135  |
| B-13   | Passive Sampler Results for the JP-4 Spill Site, Robins AFB.....  | 136  |
| B-14   | Geophysical Survey Lines in Relation to the Organic Contamination Indicated by the Ground Water and Soil Gas Data at the JP-4 Spill Site, Robins AFB..... | 138  |
| B-15   | EM-31 Vertical Dipole Data, with Instrument Oriented Perpendicular to the Survey Line at the JP-4 Spill Site, Robins AFB.....                             | 139  |
| B-16   | Apparent Resistivity Pseudosection for Line A, JP-4 Spill Site, Robins AFB.....   | 140  |
| B-17   | Apparent Resistivity Pseudosection for Line C, JP-4 Spill Site, Robins AFB.....   | 141  |
| B-18   | Apparent Resistivity Pseudosection for Line D, JP-4 Spill Site, Robins AFB.....   | 142  |
| B-19   | Model Results and Comparison of Measured and Calculated dc Resistivity and EM-31 Data for Line A, Station 10 at the JP-4 Spill Site, Robins AFB.....      | 144  |
| B-20   | Comparison of dc Resistivity Sounding Results Before and After a Rainstorm on August 21, 1986 at the JP-4 Spill Site, Robins AFB.....                     | 145  |
| B-21   | Interpreted dc Resistivity Cross Section for Line A, JP-4 Spill Site at Robins AFB.....   | 147  |
| B-22   | Interpreted dc Resistivity Cross Section for Line C, JP-4 Spill Site at Robins AFB.....   | 148  |
| B-23   | Interpreted dc Resistivity Cross Section for Line D, JP-4 Spill Site at Robins AFB.....   | 149  |
| C-1    | Fuel Farm 290 at Tinker AFB.....  | 152  |
| C-2    | Passive Soil Gas Sampling Locations, Fuel Farm 290, Tinker AFB.....   | 154  |

LIST OF FIGURES  
(CONCLUDED)

| Figure | Title   | Page |
|--------|---|------|
| C-3    | Active Soil Gas and Ground Water Sampling Locations,<br>Fuel Farm 290, Tinker AFB.....  | 155  |
| C-4    | Depths to Water Table at Fuel Farm 290, Tinker AFB.....   | 156  |
| C-5    | Thickness of Floating Product at Fuel Farm 290, Tinker<br>AFB.....  | 157  |
| C-6    | Concentrations of Benzene in Ground Water at Fuel Farm<br>290, Tinker AFB.....  | 159  |
| C-7    | Concentrations of Toluene in Ground Water at Fuel Farm<br>290, Tinker AFB.....  | 160  |
| C-8    | Concentrations of Total Hydrocarbons in Ground Water at<br>Fuel Farm 290, Tinker AFB.....   | 161  |
| C-9    | Active Soil Gas Sampling Results for Benzene at Fuel Farm<br>290, Tinker AFB.....   | 162  |
| C-10   | Active Soil Gas Sampling Results for Toluene at Fuel Farm<br>290, Tinker AFB.....   | 163  |
| C-11   | Active Soil Gas Sampling Results for Total Hydrocarbons<br>at Fuel Farm 290, Tinker AFB.....  | 164  |
| C-12   | Passive Soil Gas Sampling Results for Total Hydrocarbons<br>with a Nominal 24-Hour Exposure Time at Fuel Farm 290,<br>Tinker AFB..... | 165  |
| C-13   | Passive Soil Gas Sampling Results for Total Hydrocarbons<br>with a Nominal 96-Hour Exposure Time at Fuel Farm 290,<br>Tinker AFB..... | 166  |
| C-14   | Comparison of High Values Measured by Each Technique at<br>Fuel Farm 290, Tinker AFB.....   | 170  |
| C-15   | Comparison of Medium and High Values Measured by Each<br>Technique at Fuel Farm 290, Tinker AFB.....                                  | 171  |

# LIST OF TABLES

| Table | Title   | Page |
|-------|---|------|
| 1     | Panel of Experts.....   | 4    |
| 2     | Geology, Climate, and Contaminants at Air Force Base Study Sites.....   | 5    |
| 3     | Investigation Techniques used at Air Force Base Study Sites.....  | 6    |
| 4     | Comparison of Soil Gas Methods.....   | 13   |
| 5     | Key Results from the AFB Investigations.....  | 28   |
| 6     | Study Site and Contaminant Characteristics; Comparison of Soil Gas and Ground Water Data.....                         | 29   |
| 7     | Classification of Common Organic Contaminants.....  | 37   |
| 8     | Useful Data for Selected Organic Contaminants.....  | 64   |
| 9     | Detectability of Organic Compounds Using Soil Gas Methods..   | 69   |
| 10    | Characteristics of the 7 Geophysical Methods.....   | 74   |
| 11    | Generalized Applications of Geophysical Techniques.....   | 76   |
| 12    | Susceptibility of Geophysical Methods to "Noise".....   | 80   |
| A-1   | Measurement Techniques used at BX Service Station, Holloman AFB.....  | 97   |
| A-2   | Soil Gas and Corresponding Ground Water Concentrations of Total Hydrocarbons at the BX Service Station, Holloman AFB. | 109  |
| B-1   | Measurement Techniques used at the JP-4 Spill Site, Robins AFB.....   | 119  |
| B-2   | Electromagnetic Measurements at the JP-4 Spill Site, Robins AFB.....  | 120  |
| B-3   | EM Measured and Calculated Data: Line A, Station 10, JP-4 Spill Site. Robins AFB.....                                 | 143  |
| C-1   | Variability Information for the Passive Sampler Technique..   | 167  |
| C-2   | Passive Soil Gas Data from Badges Sorted from Lowest to Highest.....  | 168  |

## SECTION I

### INTRODUCTION

#### A. OBJECTIVES

The objectives of this study are listed below:

- to evaluate alternative techniques, other than directly sampling ground water, for detecting subsurface organic contamination under a variety of conditions;
- to recommend appropriate applications for the alternative techniques based on the field experience; and
- to recommend research that is needed to further the use of these techniques.

#### B. BACKGROUND

In 1984, the U.S. Environmental Protection Agency (EPA) Environmental Monitoring Systems Laboratory in Las Vegas, Nevada (EMSL-LV) and the Air Force Engineering and Services Center (AFESC) entered an interagency agreement concerning investigations of subsurface contamination at Air Force Installation Restoration Program (IRP) sites. Both organic and inorganic contamination were of interest, but organic contamination was emphasized. The traditional approach to these site investigations involves the installation of wells and analysis of ground water samples. This approach provides a direct measurement of the contamination at the locations sampled. However, information about the extent and degree of contamination may be limited by the number, cost and possible locations of the wells. If inexpensive, and relatively rapid reconnaissance techniques could be used as an aid to selecting the well locations, the number of wells could be reduced. This would result in significant savings in terms of costs and time.

The interagency agreement initiated studies at four Air Force bases to test indirect methods for detecting and mapping organic contamination in ground water and soil. The methods chosen for evaluation were soil gas and geophysical measurements. These measurement results then were compared to ground water data obtained during the same study. This made it possible to evaluate the performance of the soil gas and geophysical techniques for these locations. However, because of the wide variety in contaminants and geological conditions, care must be used when applying the conclusions developed from these site-specific studies to other locations. To extend the results from these studies to other site conditions, additional examples were assembled from the literature. Using all this information, general guidelines were developed for the use of these techniques in investigations of organic contamination of soil and ground water.

#### C. SCOPE

A dual approach to the project was used with activities proceeding concurrently. This approach consisted of: (1) working with a panel of experts to



broaden the ideas, approaches and experiences being used as a basis for developing the recommendations; and (2) performing site investigations to demonstrate the soil gas and geophysical techniques. This approach is described in detail in Section II.

## SECTION II

### APPROACH

#### A. OVERVIEW

Soil gas surveying is an emerging technology for detection of subsurface contamination through the use of surface techniques. The techniques of soil gas surveying are based on the measurement of volatile organic compounds (VOCs) in soil gases to detect contamination in the ground water below. VOCs dissolved in ground water vaporize into the soil atmosphere. In many situations, detectable concentrations of VOCs are present in soil gas above contaminated ground water. Because of this, soil gas surveying can be used to map contaminated ground water at a site. Since VOCs are the major components of gasoline, jet fuel number 4 (JP-4), and many industrial solvents, this technology can be useful for locating commonly occurring contamination. In these studies, active and passive soil gas techniques were tested. The results were compared to ground water analyses.

Geophysical techniques, developed for mineral, soil engineering, and oil investigations, are now being applied to hazardous waste site investigations. Techniques frequently used include direct current resistivity, electromagnetic (EM) induction, ground-penetrating radar (GPR), magnetics, and seismic methods. These methods, individually or in combination, can often provide information about geohydrologic features, locations of buried metal objects, locations of buried trenches, and mapping of conductive leachates and contaminant plumes. These applications of geophysics are well understood and documented. Electrical geophysical techniques such as EM (terrain) conductivity have been used on a number of occasions to directly detect organic contamination (References 1, 2, and 3). However, these methods generally have not been accepted for routine use because the physical response is not well-understood. The use of GPR and complex resistivity to directly detect organic contamination has been documented for a number of locations (Reference 4). Geophysical techniques are subject to interferences from a variety of sources, depending on the technique. These interferences, which include the presence of metal objects, pipelines, powerlines, radio transmissions, and ambient noise, may prevent the collection of useful data at a particular location. In this study, all the methods mentioned above except ground-penetrating radar were demonstrated at one or more locations. At most bases, the geophysical techniques were used to determine physical characteristics such as depth to bedrock, or depth to the water table. In some cases, geophysical methods were used to locate buried metal objects. The direct detection of organic contamination was also attempted using EM and dc resistivity techniques. In this report, the emphasis will be on using soil gas and geophysical techniques to directly detect organic contamination.

#### B. PANEL OF EXPERTS

A panel of experts was chosen to provide advice on site investigation approaches. These experts and their fields of expertise are listed in Table 1. Each expert was assigned the task of describing the approach he used for investigations at hazardous waste sites. These approaches were compiled for the

entire group to review and discuss at a 2-day meeting. The resulting information was of value to the field studies in progress and, where appropriate, has been included in this report.

TABLE 1. PANEL OF EXPERTS.

| Name                               | Affiliation                                     | Area of expertise   |
|------------------------------------|---|---|
| Dr. John Cherry<br>Hydrologist     | Geoflow, Limited<br>Waterloo, Ontario, Canada   | organics in aquifers, wells,<br>ground water sampling               |
| Dr. Gary Robbins<br>Hydrologist    | Woodward-Clyde Associates<br>Santa Ana, CA      | organics in aquifers, soil<br>gas, soil core head space<br>analysis |
| Dr. Thomas Spittler<br>Chemist     | U. S. EPA, Region 1<br>Lexington, MA            | soil gas analysis,<br>analytical chemistry                          |
| Dr. Donn Harrin<br>Hydrologist     | Tracer Research Corp.<br>Tucson, AZ             | soil gas analysis   |
| Dr. Gary Olhoeft<br>Geophysicist   | U. S. Geological Survey<br>Denver, CO           | electrical geophysical<br>techniques                                |
| Mr. Wayne Saunders<br>Geophysicist | Camp, Dresser, and McKee,<br>Inc. Annandale, VA | electrical geophysical<br>techniques                                |
| Dr. Aldo Mazzella<br>Geophysicist  | U. S. EPA, ENSL-LV<br>Las Vegas, NV             | electrical geophysical<br>techniques                                |

#### C. SELECTION OF STUDY AREAS FOR INVESTIGATION

The other part of the project consisted of field tests and qualitative comparisons of soil gas and geophysical results to ground water data. Geophysical techniques also were used as part of the site characterization. Four Air Force bases were chosen for these investigations after review of preliminary information from a total of 18. The selection criteria included the following:

- presence of JP-4, gasoline, or solvent contamination from a relatively recent spill (within the last 20 years);
- type of source of contamination; e.g., surface spill, pipeline leak, fire training area;
- depth to aquifer less than 100 meters;
- type of geology, e.g., karst, alluvium, marine sand; and type of soil;

- conductivity of aquifer;
- ease of access both to the study area, and the ground surface; sites with contamination under large paved areas were excluded; and
- number of wells already in place, delineating contamination.

The bases selected are listed in Table 2. Each base provides differing geology, climate, depth to water table, and contaminants, thus, representing a variety of situations for performing the comparisons. Areas with different types of contamination were sometimes present at one base. To maximize the information gained, multiple site investigations were performed. This occurred at Phelps-Collins Air National Guard Training Base (ANGTB), Holloman AFB, and Robins AFB. The methods used in the studies are listed and described in Section III, "METHODS." The studies and results are described in detail in individual site reports (References 5 - 8). Key examples from these site investigations are presented in Appendices A, B, and C, and results are summarized in Section IV, "FIELD INVESTIGATIONS."

TABLE 2. GEOLOGY, CLIMATE, AND CONTAMINANTS AT AIR FORCE BASE STUDY SITES.

| Base                    | Geology                | Climate | Contaminant                             |
|-------------------------|------------------------|---------|---|
| Holloman AFB            | sand, interbedded clay | arid    | gasoline, JP-4, solvents                |
| Phelps Collins<br>ANGTB | karst                  | humid   | solvents, JP-4, buried metallic objects |
| Robins AFB              | marine sand            | humid   | JP-4, solvents                          |
| Tinker AFB              | clay                   | humid   | JP-4                                    |

This series of studies was intended to help develop a hierarchy of techniques which could be logically adapted and applied to detect contamination for a variety of site conditions. However, the results from the field studies fit better into a framework of broad guidelines rather than into a detailed strategy which ranks techniques. These broad guidelines are provided in Sections V, VI, and VII, "GENERAL CONSIDERATIONS FOR SITE INVESTIGATIONS," "PLANNING A SOIL GAS INVESTIGATION," AND "PLANNING A GEOPHYSICAL INVESTIGATION," respectively.

## SECTION III

### METHODS

#### A. INTRODUCTION

This section serves two purposes. It summarizes the techniques applied during the field studies and briefly reviews key characteristics of these techniques, providing references to detailed descriptions in the literature.

#### B. SUMMARY OF METHODS USED AT AIR FORCE BASES

A complete summary of the techniques considered for use in the field investigations is provided in Table 3. The goal of applying these techniques was to either characterize the hydrogeology or determine the distribution of contaminants so that results from each of the selected techniques could be compared. Soil gas and ground water sampling were conducted at all bases; the EM and dc resistivity measurements were performed at three of the four bases.

TABLE 3. INVESTIGATION TECHNIQUES USED AT AIR FORCE BASE STUDY SITES.

| Technique                                  | Phelps-Collins | Holloman | Robins | Tinker |
|--|----------------|----------|--------|--------|
| Sampling ground water from existing wells  | yes            | yes      | yes    | yes    |
| Sampling ground water using soil gas probe | no             | yes      | yes    | no     |
| Soil cores                                 | no             | no       | no     | no     |
| Active soil gas sensing                    | yes            | yes      | yes    | yes    |
| Passive soil gas sensing                   | no             | no       | yes    | yes    |
| DC resistivity                             | yes            | yes      | yes    | no     |
| Electromagnetic induction                  | yes            | yes      | yes    | no     |
| Seismic                                    | yes            | no       | no     | no     |
| Ground-penetrating radar                   | no             | no       | no     | no     |
| Complex resistivity                        | no             | no       | no     | no     |
| Aerial photography                         | no             | no       | no     | no     |

Some of the techniques listed were not used in the site investigations, although they might have provided useful information. In certain cases, the situations were not appropriate, while in others, the equipment could not be easily obtained. For example, because of expense and because sites were chosen with wells already available, no new wells were installed. Similarly, no soil cores were obtained, although this technique would normally be part of an investigation. Ground-penetrating radar (GPR) and complex resistivity also were not demonstrated in the field. Cost and scheduling problems precluded the use of ground-penetrating radar at Robins AFB where it would have been appropriate. It would be useful to apply this technique at Robins at a later date. Complex resistivity was not appropriate for three of the four study sites. Thick clay was present at the fourth site, Tinker AFB, but the presence of underground pipelines and tanks precluded the use of the technique. Aerial photography would have been used at all the sites if suitable maps and historical information had not been available.

## C. SOIL GAS TECHNIQUES

### 1. Theory

Soil gas sampling and analysis are available commercially. The technique has several common variations, but the key elements are the collection of a sample of vapor from the soil and the detailed analysis of the sample with a gas chromatograph (GC) for key compounds which indicate the presence of contaminants. The theory of behavior of volatile organic compounds (VOCs) in the subsurface provides a basis for understanding the technique more completely. The discussion below is adapted from References 9 and 10.

When volatile organic compounds are present in the subsurface, either in an organic liquid phase or dissolved in ground water, several processes, under both thermodynamic and kinetic control, can take place. In the saturated zone, the VOCs can undergo sorption to organic matter in the soil, liquid diffusion, vertical and horizontal mixing due to dispersion, biotransformations, and chemical reactions (Reference 9). In the unsaturated zone, the vapors from these VOCs can undergo gas-phase diffusion, vapor/sorption equilibria, vapor/solution equilibria, biotransformations, and chemical reactions. In the intermediate zone or capillary fringe, the potential for any of the above processes can exist. By definition, the capillary fringe is fully saturated. The water there is held by capillary forces or soil suction, and so is under less than atmospheric pressure. In actuality, heterogeneity in the size and shape of vadose zone materials can result in the presence of adjacent air-filled and water-filled channels in the capillary fringe.

Although many processes can affect volatile organic compounds in the subsurface, the list of processes important to soil gas surveying is limited. To detect VOCs in soil gases above contamination, the rate of introduction of VOCs into the soil atmosphere must be sufficient to maintain a measurable VOC concentration there. That will occur only if the rate-limiting step in vertical transport of VOCs from the contamination source to the atmosphere is diffusion through the vadose zone. Under these conditions, the VOC vapor concentration above the capillary fringe/vadose zone interface will be at a concentration controlled by a dynamic vapor/solution equilibrium, while VOC concentration in soil gases between there and the soil surface will be determined by the rate of diffusion of the gases through the soil (Reference 9).

Fick's Laws describe the process of diffusion (Reference 9); these equations have been modified extensively to describe diffusive flow through porous media. Fick's Law for volatile organic compound diffusion in air through a unit area, as corrected for available air-filled pore space is

$$\text{mass flow} = -D_a P (C_s - C_a) / Z \quad (1)$$

where  $D_a$  is the gas-phase diffusion coefficient,  $P$  is the air-filled porosity.  $C_s$  is the gas-phase VOC concentration at the capillary fringe.  $C_a$  is the concentration at the soil surface, and  $Z$  is the depth from the surface to the capillary fringe. Millington and Quirk have derived an expression based on Fick's Law for diffusion of gases through soils, modified for the tortuosity (nonlinearity) of diffusion paths through porous media (Reference 9). In that description of diffusion in soils, the gas-phase diffusion coefficient,  $D_a$ , for the diffusing compound is modified for tortuosity by multiplying it by  $P$ , the air-filled porosity of the soil raised to the 4/3 power. Equation 1 modified for tortuosity becomes

$$\text{mass flow} = -D_a P^{1/3} P (C_s - C_a) / Z \quad (2)$$

for dry soil, where  $P^{1/3}$  is the term incorporated to describe the tortuosity of porous media. Equation 2 predicts a linear concentration gradient with depth under homogeneous conditions. A strong linear-depth-dependence of the VOC concentration in soil gas has been observed in a number of field and laboratory studies. Nonkinetic factors, such as equilibrium sorption on soil, are not relevant to discussion of the kinetically controlled VOC concentrations in the vadose zone that exist when soil gas surveying is applicable.

The volatile organic compound concentration gradient between the atmosphere and the soil gas in contact with the capillary fringe is the driving force for the vertical transport of VOCs through diffusion. The concentration of VOC in the gas phase in contact with the capillary fringe is dictated by a dynamic equilibrium between the dissolved and the gas phase VOC. The physical-chemical expression which describes this equilibrium is Henry's Law (Reference 9). The Henry's Law constant of a VOC can be obtained by dividing the vapor pressure of the pure VOC by its solubility in distilled water. The relationship of Henry's Law constants to the likelihood of detecting selected compounds using soil gas techniques is discussed in Section V. Henry's Law constants for a number of compounds of interest are provided there. However, these values should only be used for guidance on the relative suitability of a VOC for detection by soil gas measurements. This is because conditions encountered in the field such as ambient pressure, organic content of the soil, temperature, and ionic strength of the water, are different from the conditions used to determine the tabulated values.

Figure 1 shows three possible volatile organic compound concentration depth profiles. Unsaturated zone VOC concentrations vary linearly with depth as mentioned in the discussion of Fick's Law. The rate of change of the profile depends on whether the flux rate is limited by gaseous diffusion in the vadose zone (Case 1) or by dispersion in the saturated zone (Case 3). Case 2 shows intermediate behavior. In Case 1, the rate of supply of the VOC of interest due to saturated zone dispersion is very high, compared to the rate of diffusion in the unsaturated zone. In Case 3, the rate of supply of the VOC of interest due to saturated zone dispersion is very low, compared to the rate of diffusion

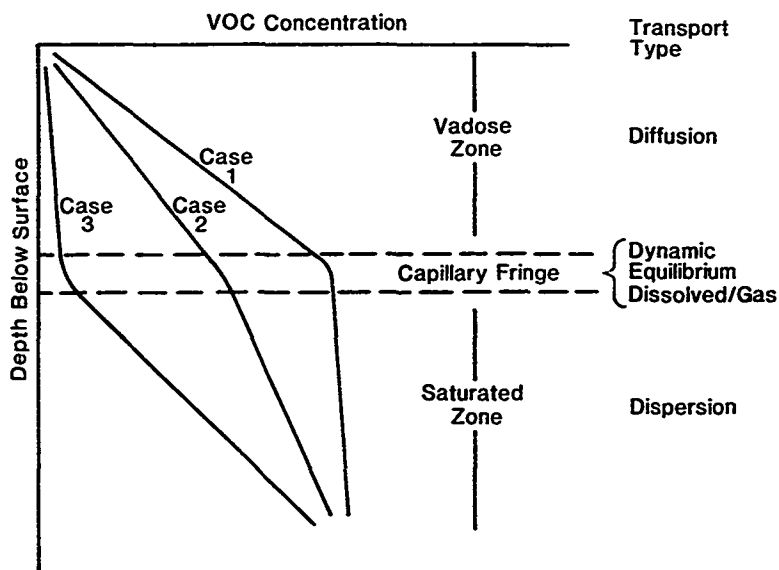


Figure 1. Predictions of Volatile Organic Compound Concentration in the Subsurface (adapted from References 9 and 10).



in the unsaturated zone. Thus, for a dispersion-limited system with a high unsaturated zone diffusion rate (as shown in Case 3), the VOC concentration in the soil gas can be very low.

## 2. Overview of Techniques

A soil gas sample can be obtained in a number of ways. It can be removed from the soil by inserting a probe and extracting a sample under vacuum with a syringe. Probes can be inserted into the ground with hammers or hydraulic rams, reaching depths of 3 to 5 meters, depending on soil type (References 11 - 17). Alternately, a sample can be collected by burying a collector with an absorbent such as activated charcoal (References 9 and 18). After allowing a diffusion time which ranges from hours to days, the collector is removed.

Once the sample is collected, it is analyzed, using a gas chromatograph, either immediately in the field or after a delay, in the laboratory. Laboratory analysis is more time-consuming because of the additional handling required. The real-time analysis allows for selection of additional sampling locations so that contamination can be mapped more completely than would occur if the same number of sample points were used in a regular grid.

The detection methods used for analysis of soil gas samples are listed below. For comparison purposes, the sensitivity of each method is rated relative to that of the flame ionization detector in terms of detectable mass flow rate (References 17, 19, and 20). These methods include:

- Flame ionization detector (FID) for the full range of organic compounds; can detect 4 picograms of carbon per second;
- Electron capture detection (ECD) for selective detection of halogenated hydrocarbons; can detect 0.01 picograms per second of material, which depending on the material can be 100 to 1000 times more sensitive than an FID; it is more sensitive to iodine-containing materials than similar materials with chlorine or fluorine;
- Hall Electrolytic Conductivity detector (HECD) for the specific detection of halogenated species, nitrogen containing organics, or sulfur containing organics; can detect 0.5 picograms chlorine per second; this is 10 times more sensitive than an FID, and 10 times less sensitive than an ECD;
- Photoionization detector (PID) for the aromatic hydrocarbons and sulfur species; can detect 10 to 100 picograms per second of aromatic material or 50 to 100 picograms per second of polyaromatic material, which is slightly more sensitive than an HECD or FID; and
- Flame photometric detector (FPD) for sulfur and phosphorus compounds; can detect 1 picogram per second of phosphorous or 100 picograms per second of sulfur; depending on the material, can range from as sensitive as to 100 times less sensitive than an FID.

For comparison, the mass spectrometer typically used in laboratory analyses in combination with a gas chromatograph is as sensitive as an FID.

Some initial indication of contamination can be obtained with a commercially available organic vapor analyzer (OVA) but, since these type devices do not distinguish between hydrocarbons and chlorinated solvents, the results can be confusing, if both are present. In addition, these devices are not as sensitive as field gas chromatography. Therefore, contamination may not be detected.

Soil gas techniques may be influenced by airborne and surface VOCs, as well as underground VOCs, thus, requiring care when the measurements are performed. Also, permeability variations in the site from utility corridors, clay layers, and fractures will modify the soil gas results, requiring careful interpretation. Driving gas sampling probes into the ground to depths of 1 to 3 meters (3 to 9 feet) provides a safety hazard because the probes may puncture underground utilities or buried drums if their locations are not precisely known. Two soil gas sampling techniques were used in the studies at the bases. The techniques are described below.

#### a. Active Soil Gas Sampling

In active sampling, a hollow pipe is driven into the ground to a prescribed depth and soil gases are pulled through it to the surface. The sample is then analyzed by gas chromatography at or near the sampling location. This method offers the benefit of immediate results as the survey progresses, an attractive feature which allows the sampling plan to be changed on the basis of results. In addition, preliminary measurements can be performed to allow investigators to optimize certain survey parameters, such as sampling depth. An additional advantage of this approach is the presence of analytical equipment, to perform onsite screening of soil and ground water samples. The drawback of this approach is that it requires the presence of sophisticated analytical and sampling equipment. The presence of this equipment, a specialist to operate and maintain it, and associated support systems such as generators and gases, make the technology somewhat expensive. This technique has been used successfully at a large number of sites.

Active soil gas investigations were conducted at a variety of locations at all four bases. In determining the extent of the contaminated areas, the samples were analyzed for methane, benzene, ethyl benzene, toluene, xylene, total nonmethane hydrocarbons, and halogenated organics. The contractor used an analytical field van, equipped with two Tracor GCs with FIDs and two computing integrators for real-time sampling and analysis of the soil gas. This van was also equipped with a specialized hydraulic ram mechanism used to drive and withdraw the sampling probes. The probes consisted of 2.1-meter (7-foot) lengths of 1.9-centimeter-diameter (3/4-inch) steel pipes fitted with detachable drive points. A hydraulic hammer was used to assist in driving the probes through hard soil.

Soil gas samples were collected from depths ranging from 0.6 to 2.4 meters (2 to 8 feet) in the ground. The key features are shown in Figure 2. The aboveground ends of the sampling probes were fitted with a steel reducer and a length of polyethylene tubing leading to a vacuum pump. Approximately 5 to 10 liters of gas were evacuated with the vacuum pump, to assure a representative sample. Samples were collected by inserting a syringe needle through a silicone rubber segment, just above the reducer, in the flowing evacuation line and down into the steel probe. Ten milliliters (mL) of soil gas were collected

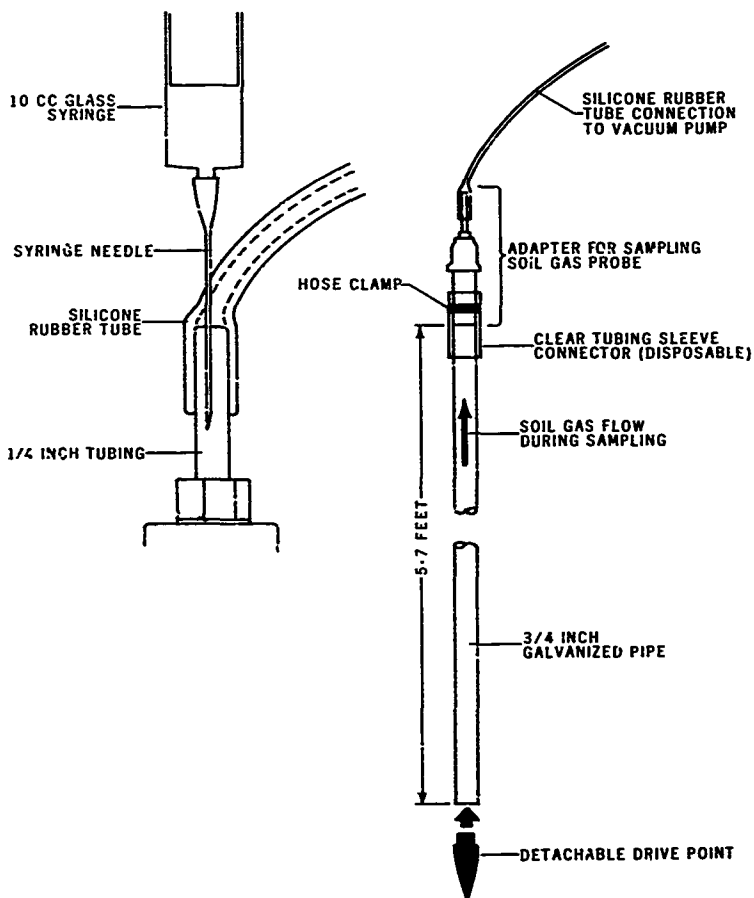


Figure 2. Features of an Active Soil Gas Sampling System.  
(Courtesy of Tracer Research Corporation)

for immediate analysis with one of the GCs. The soil gas was subsampled in volumes ranging from 1 microliter ( $\mu\text{L}$ ) to 2 mL, depending on the expected concentrations of volatiles. The syringe needles were used once and discarded; the syringes were cleaned and baked after each use. Using the experiences at the four bases as a guide, the cost for soil gas sampling and analysis for 50 locations in one area is \$7,500. Thus, the cost per sample location is approximately \$150. Features of active soil gas sampling are summarized in Table 4.

TABLE 4. COMPARISON OF SOIL GAS METHODS

| Active Sampling with Gas Chromatograph on Site   | Passive Badge Sampling with Analysis at Laboratory  |
|--|---|
| Site specific information, such as sampling depth, is determined at outset of study, within 1 to 2 hours | A calibration study is needed before full-scale study, to determine optimum sampling time and depth             |
| Insertion of probes to depths of 2 to 3 meters is simple in most soils                                   | Insertion of samplers at depths greater than 1 meter is difficult   |
| Analysis of samples is immediate, with results in approximately one hour                                 | Analysis of samples is delayed, by shipping and laboratory holding times  |
| Sampling plan can be changed as results are obtained, leading to fewer sampling locations overall        | Additional sampling sites are selected after each sampling and analysis cycle is complete                       |
| One sampling and analysis effort is usually sufficient to locate and map contamination                   | At least two sampling and analysis efforts are needed (calibration study and full-scale studies as appropriate) |
| Sampling activity at a specific location is completed in approximately one hour                          | Samplers must not be disturbed during the sampling period typically several days to a week                      |
| Complex technology and skilled operators may not be available  | Field personnel need minimal skill to install and remove samplers   |
| Cost is approximately \$150 per sample   | Cost is approximately \$93 per sample   |

## b. Passive Soil Gas Sampling

At least two passive soil gas sampling techniques are in use. Each technique uses the same sampling technique, shallow burial in soil, but the collectors and analysis are different. One technique uses a thin ferromagnetic wire coated with adsorbent charcoal. When the sample is returned to the laboratory, the wire is heated in a vacuum and the desorbed compounds are analyzed by Curie point mass spectrometry (Reference 18). These Petrex™ samplers cost \$85 each for quantities less than 100 and \$75 for quantities greater than 100. The cost of the samplers includes analysis by mass spectrometry. The other technique uses commercially available, charcoal adsorbent, 3M™, organic vapor monitor badges originally designed to be worn by personnel for environmental health and safety reasons (Reference 9). These badges cost \$7 to \$10 each, based on the quantity purchased. This method was used at Robins AFB and Tinker AFB to demonstrate the use of this technique in sand and clay geologic environments, respectively.

The charcoal adsorbent passive sample relies on the principle of diffusion to create a VOC mass flow onto the adsorbent. The VOCs from the surrounding air diffuse to the collection surface in response to a concentration gradient. This collection rate is a function of the diffusion coefficient,  $D$ , of the VOC of interest; the area,  $A$ , of the adsorbent surface; the length,  $d$ , of the diffusion path; the ambient concentration of VOCs in the air,  $C_1$ ; and the VOC concentration at the adsorbent surface,  $C_0$ . If the charcoal is not saturated, the concentration at the adsorbent surface will be zero; thus the collection rate,  $m$ , is equal to a constant unique to a given compound and sampler (the volume of air sampled per hour) times the ambient concentration, i.e.,

$$m = D(A/d)C_1 \quad (3)$$

volumes of air sampled have been tabulated by compound for industrial hygiene applications. Solving for the ambient concentration,

$$C_1 = m(d / AD) \quad (4)$$

This type sampler has a known response to a broad range of volatile organic compounds for a variety of temperatures, relative humidities, and concentrations (Reference 9).

To collect a soil gas sample, the badges were installed in sampling manifolds constructed from clean, 0.95-liter (1-quart) aluminum cans. The sampler and manifold are depicted in Figure 3. The manifold-sampler combination was placed in a shallow hole dug into the ground, covered with soil, and left in place for a set time, based on estimated ambient concentrations. Passive samplers should generally be buried at least 0.6 meters (2 feet) below grade to minimize the effects of atmospheric air dilution of soil gases. The samplers were then removed, sealed, and returned to the laboratory. When using the Petrex™ samplers, the installation method is similar; a shallow hole is dug, the sampler, an open test tube with the wire and charcoal element inside, is placed open-end-down in the bottom of the hole and the soil is replaced over it. For both techniques, the rate at which samplers may be installed depends on the hardness of the soil and the distance between samplers. At the 2-acre Tinker AFB study area, 62 badges were installed in 5 hours in hard clay soil by one person. A conservative estimate of installation time is 30 samplers per

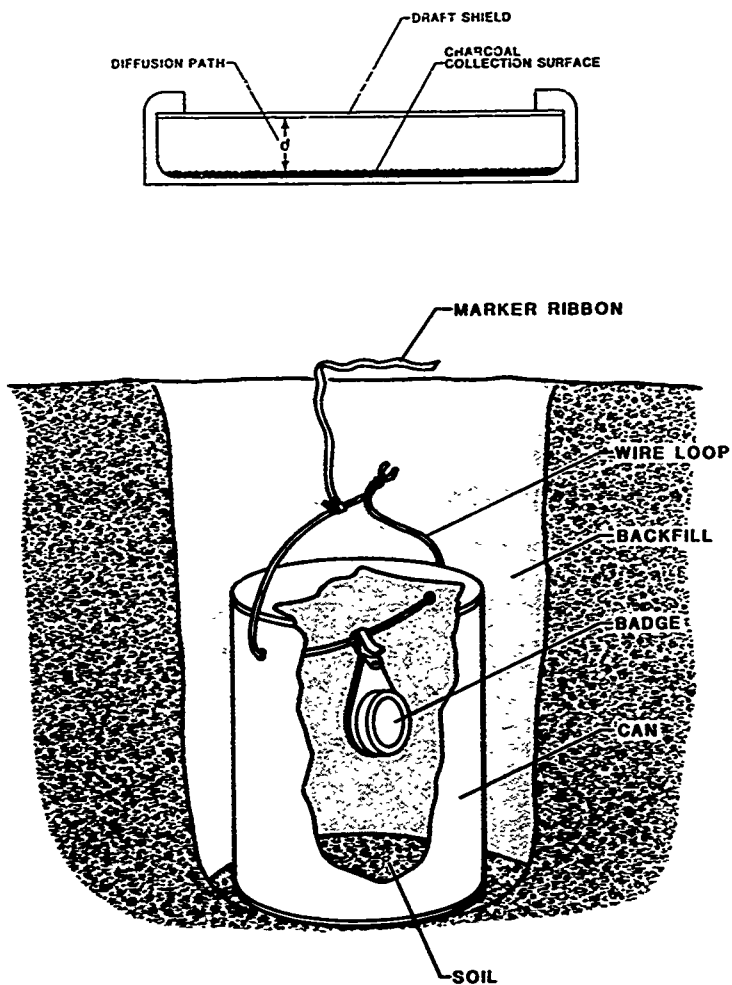


Figure 3. Passive Soil Gas Sampling Badge and Manifold (after Reference 9).

person per day. The time to remove the samplers is approximately half that to install them. A person must be available to perform the badge removals when the selected sampling period is over, typically several days to a week after installation.

At the EMSL-LV laboratory, the VOCs were solvent-desorbed and the resulting solution was analyzed by gas chromatography. The procedures used are described in References 7, 8, and 9. The estimated cost per analysis for the charcoal badges is \$75 to \$100, based on this experience. Analytical services for these badges are offered as a service by a number of companies at costs ranging from \$48 to \$58 depending on the type of analysis requested. Analysis of one to three compounds can be requested. The total cost for using badges will be higher due to the costs of the badge itself, labor to install and remove the badges, and shipping to the laboratory.

To perform a full-scale investigation using the passive soil gas technique, it is desirable to determine an optimum exposure time and depth for the study area. This is accomplished by performing field calibration tests to learn whether the technique can be used with confidence to detect contamination at a site. This process can easily use 30 badges depending on the complexity of the site, i.e., 2 depths x 3 sampling intervals x 5 locations ranging from contaminated to uncontaminated.

The disadvantage of passive samplers is that delays are caused by transport and analysis at the laboratory. To be assured of obtaining complete information about a site, additional samples are required, compared to active sampling. It is not possible to alter the investigation plan in progress as data become available. This increases the costs.

The total cost per badge sample, including badge (\$10 each), labor (\$8 each using \$20 per hour hourly rate), and analysis (\$75 each) is approximately \$93. The comparable cost of the Petrex TM samplers including badge and analysis (\$85 each), labor (\$8, using the same costs as above), is also approximately \$93. Shipping costs and field calibration testing costs are not included in either example and can be expected to increase the costs further. These methods cost approximately \$50 less than the active sampling technique. Features of the passive sampling technique are listed in Table 4. The site investigator must balance these reduced costs against the delays and the additional samples which will be required using the passive techniques.

## D. GEOPHYSICAL TECHNIQUES

### 1. Introduction

Geophysical techniques measure a variety of properties of the earth (Reference 21). For example, ground-penetrating radar is a reflection technique using high frequency electromagnetic waves, which are reflected off subsurface features. Electromagnetic induction measures the electrical conductivity of the subsurface with lower frequency electromagnetic waves. Direct current resistivity measures subsurface electrical resistivity which is related to conductivity. Seismic refraction involves transmission of sound waves into the ground. Using measurements of the travel time of the waves, the thicknesses

and depths of geological layers can be established. Magnetometry detects anomalies in the earth's magnetic field caused by ferrous objects such as iron or steel. These techniques can be used for defining natural geologic features; locating conductive leachates and contaminant plumes; locating buried trenches and locating metal objects. This section briefly reviews the characteristics of these methods.

## 2. Electromagnetic Induction

Electromagnetic induction is a geophysical technique that is readily available commercially and quickly acquires data for electrical conductivity over a large area. Data are acquired by transmitting a signal from a transmitter coil and measuring the perturbation in the signal at the receiver coil. The perturbation is due to the presence of nearby conductive materials such as metal objects and the earth, and is proportional to the conductivity of these materials. A conceptual diagram of an EM system is provided in Figure 4. Depth of electromagnetic penetration is a function of coil spacing, signal frequency, and electrical conductivity. These depths are typically on the order of meters to tens of meters with hand-held instruments. A variety of commercially available instruments can be used to explore different depths, depending on the conductivity of the surface. If the site relief i.e., change in surface elevation across the study site, is greater than 1 meter, the data may require topographic correction. This correction accounts for the changing distance from the surface of the earth to the water table, which is a conductive feature. Nearby utilities, gas pipelines, power and telephone lines, radio and radar transmitters, and metal fences and debris can interfere with the measurements. Variations on an electrical conductivity map can represent changes in porosity, water saturation level, salinity of the ground water, or the presence of clay lenses. Such a map can generally illustrate the uniformity of a site subsurface. Basic sources of information about EM include References 21 - 24.

## 3. Direct Current and Complex Resistivity

Direct current resistivity is also commercially available. The dc resistivity method makes physical contact with the earth using shallow (<0.3-meter) electrodes. By establishing a current between two electrodes and measuring the potential difference between a second set of electrodes, the apparent resistivity of the earth is measured. A conceptual diagram of a dc resistivity system is provided in Figure 5. Interpretation of these data can indicate various layers, which may correspond to the depths of the water table, aquitards, and bedrock. The geometry of the electrode arrays and spacings determines the depth of investigation. Increasing the electrode spacing samples a greater depth and volume of earth, as shown in Figure 6. The technique requires more time than EM to cover a given area. Resistivity soundings, however, can give more detailed depth profiles than commercially available EM methods. The technique requires topographic correction and may also be subject to interference from utilities. It is possible to perform dc resistivity measurements without interference nearer to metal objects such as fences, than EM measurements can be performed. The direct current resistivity method can be used with a single spacing or a series of spacings (as described above for the EM method) for profiling and mapping, at one depth or a series of depths. Basic sources of information about dc resistivity include References 21, 24, and 25.



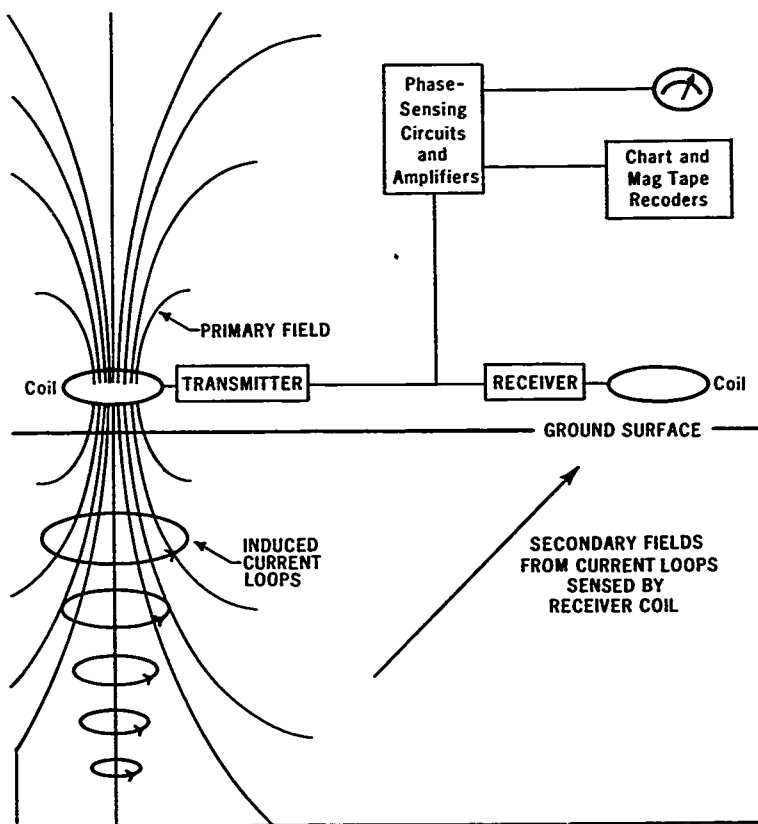


Figure 4. Conceptual Diagram for an Electromagnetic (EM) Induction System (adapted from Reference 21).

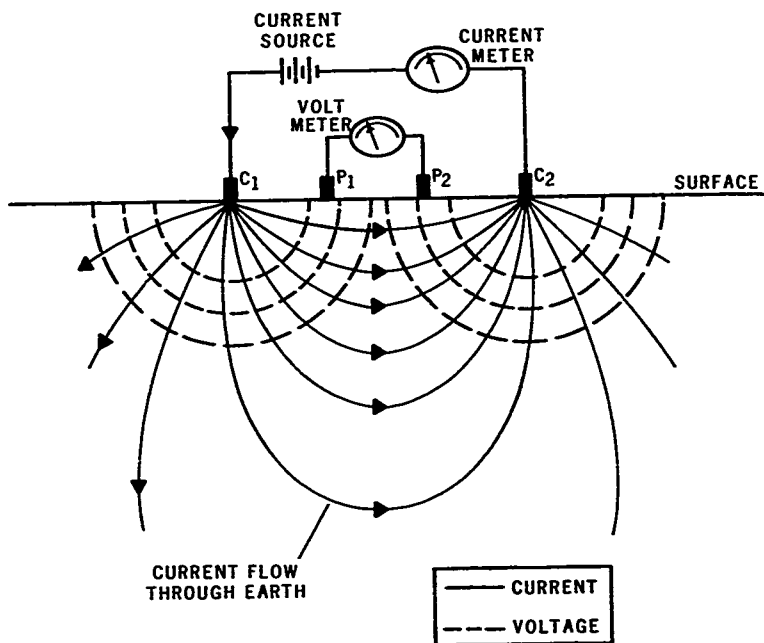


Figure 5. Conceptual Diagram for a Direct Current Resistivity System (adapted from Reference 21).

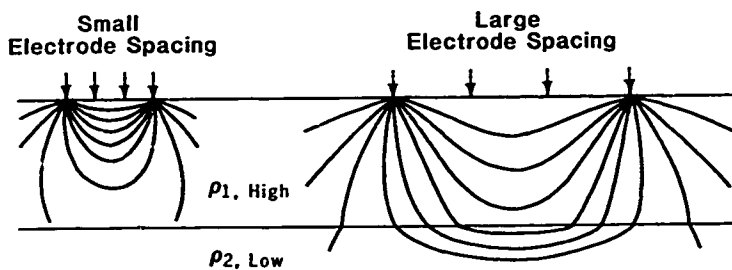


Figure 6. Increased Electrode Spacing Samples Greater Depth and Volume of Earth (adapted from Reference 21).

Complex resistivity is the technique of measuring resistivity in both magnitude and phase as a function of frequency (sometimes called induced polarization). The technique requires costly equipment and more time than conventional resistivity and is thus more expensive. However, the frequency-dependent measurement gives information about active chemical processes in the earth as well as the same information acquired by EM or conventional resistivity. This technique has shown the ability to detect and map organic materials in the presence of clay by mapping clay-organic reactions. There are few available commercial sources for this technique. Basic sources of information about this technique include References 4, and 26 - 28.

#### 4. Ground-Penetrating Radar

Ground-penetrating radar (GPR) is readily available commercially, rapidly provides very high spatial resolution over a large area, can make useful measurements close to utilities, but is more expensive than EM or resistivity. GPR emits electromagnetic waves at frequencies selected in the range of 80 to 1000 megahertz. The wave fronts are reflected when they encounter contrasts in the dielectric constant, such as the water table, bedrock, and clay layers. This type system is shown conceptually in Figure 7. The reflected waves are plotted as a function of depth and topographic correction is required. The depth of penetration is controlled by the intrinsic conductivity of the earth, the amount of inhomogeneity in the earth, and the amount of clay and water present (References 4, and 29). In clay-free sand with resistivity above 30 ohm-meters, the ground-penetrating radar can map bedding and stratigraphy, water tables, bedrock interfaces, and other features with dielectric contrasts at a resolution of a few centimeters to depths of 30 meters (Reference 30). Five to 10 weight percent montmorillonite clay will reduce the depth of penetration to less than one meter. As dielectric contrasts do exist between most earth materials and many organic substances, it is possible to detect certain kinds of organics with ground-penetrating radar (References 4, 31 and 32). Basic information may be found in References 21 and 32.

#### 5. Seismic Techniques

Seismic compressional and shear wave, reflection and refraction techniques are readily available commercially and can be used to determine stratigraphic and lithologic layer thicknesses and depths. Seismic waves in the subsurface travel at different speeds in various types of soil and rock and are refracted and reflected (bent) at interfaces between layers. Geophones spaced at intervals on the surface can detect these waves; from this information, travel time can be determined. This enables the number and thickness of layers as well as their depth and the seismic velocity of each layer, to be determined also. Topographic correction is required. A conceptual diagram of the seismic refraction technique is shown in Figure 8. Seismic refraction works if each successively deeper layer has a higher propagation velocity, i.e., is more dense. Both seismic techniques can provide information at great depths, but they do not easily provide information on features shallower than 3 meters (10 feet). Seismographs and geophones are commercially available. A sledge hammer striking a steel plate on the ground, or if there is no explosive danger, a specialized shotgun or explosives, are examples of suitable sources of seismic energy. Any nearby loud noise source such as a busy highway or construction may interfere with the survey. Seismic techniques are not as rapid as EM and GPR. The seismic techniques work best in competent materials and perform very

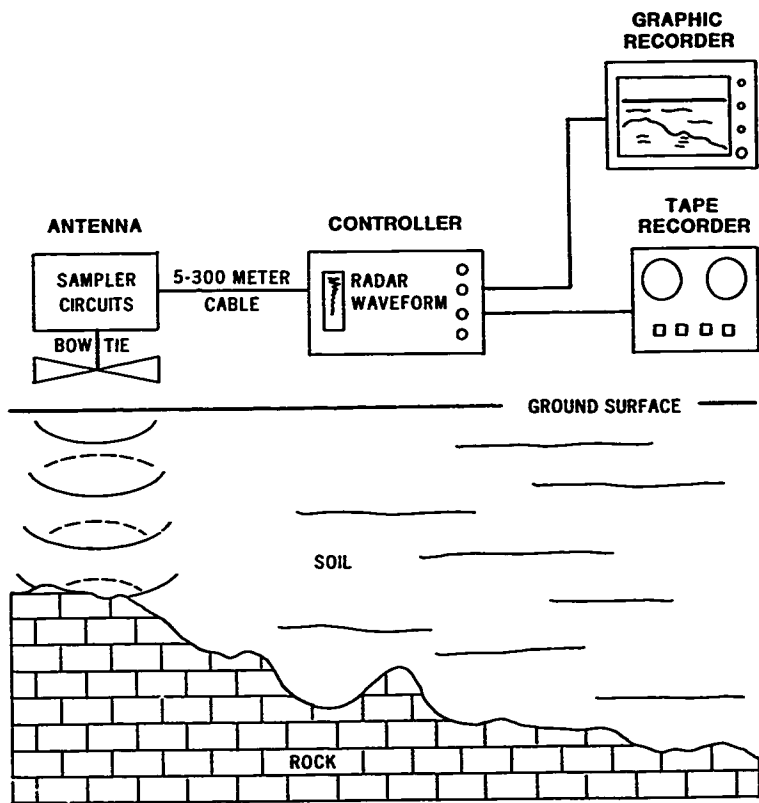


Figure 7. Conceptual Diagram for a Ground-Penetrating Radar System (adapted from Reference 21).

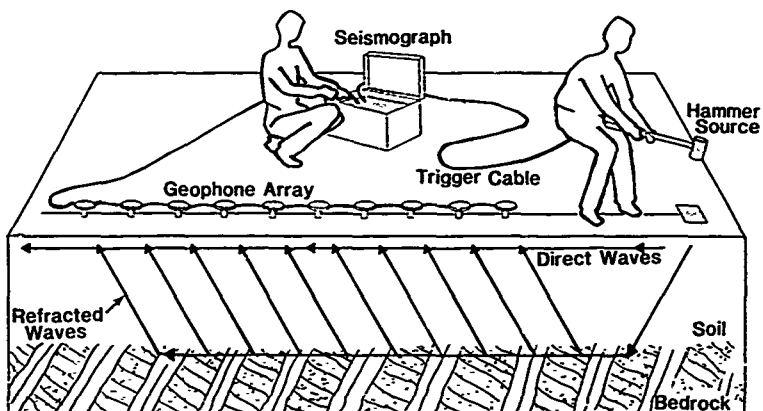


Figure 8. Conceptual Diagram of a Seismic Refraction System (adapted from Reference 21).

poorly in loose materials. In clay-free sandy soils, GPR will work better than seismic techniques and with higher resolution. In clay-bearing soils, seismic techniques will work better than GPR. Marine seismic techniques are useful in mapping stratigraphy below rivers and lakes. As there are no acoustic contrasts between geological materials and organic contaminants, seismic techniques cannot directly map organic contamination. Basic information on seismic techniques is in References 21, 33, and 34.

## 6. Magnetometry

Magnetometry is an inexpensive, readily available technique which measures the intensity of the earth's magnetic field. The presence of ferrous objects such as iron drums creates a perturbation in the local strength of the earth's magnetic field. The change in the strength is proportional to the mass of the object. Detection of these ferrous objects depends on the mass, magnetic properties, orientation, and depth of the object; the intensity and direction of the earth's magnetic field; and the sensitivity of the magnetometer. A conceptual diagram of a magnetometer is shown in Figure 9. A large number of magnetometers are available commercially; two common types are the fluxgate and proton magnetometers. The fluxgate measures a component of the magnetic field and the proton magnetometer measures the total magnetic field. Magnetic field measurements can be made in two ways; the magnetic field can be measured, or a difference, or gradient, can be determined between two different points. Total field measurements are more sensitive but are also more susceptible to noise than the gradient measurements (Reference 21). Cultural features such as buried pipes; metal buildings; and magnetic properties of the soil may interfere with the measurements. According to Reference 18, this technique can detect buried drums, define boundaries of trenches filled with drums or other steel objects; and locate iron pipes or tanks. Basic information about these techniques can be obtained from References 21 and 35.

## 7. Detection of Organic Contamination

A number of physical mechanisms can make the detection of organics by geophysical techniques possible. For example, in most near-surface rocks, the dominant electrical conduction mechanism of current is through the water in the pore spaces of the formation. If the electrolyte is replaced by a high resistivity fluid, such as a petroleum hydrocarbon, the resistivity of the formation may increase. However, the presence of clay minerals and buried metallic objects, such as pipes, can also significantly alter the electrical resistivity of the subsurface. These provide competing mechanisms to the conduction through the pore space. One of the objectives of the studies at Holloman and Robins AFBs was to determine whether any change in resistivity due to the presence of gasoline or JP-4 was detectable over manmade or naturally occurring conditions, such as changes in the porosity, saturation level, the presence of clay minerals, or buried metallic objects. For these studies, EM and dc resistivity measurements were performed. Other techniques which may be of use for locating subsurface organics are ground-penetrating radar and complex resistivity.

The remainder of this section on ground-penetrating radar and complex resistivity is adapted from Reference 4, written by Dr. Gary Olhoeft, a member of the panel of experts. Ground-penetrating radar uses the propagation of

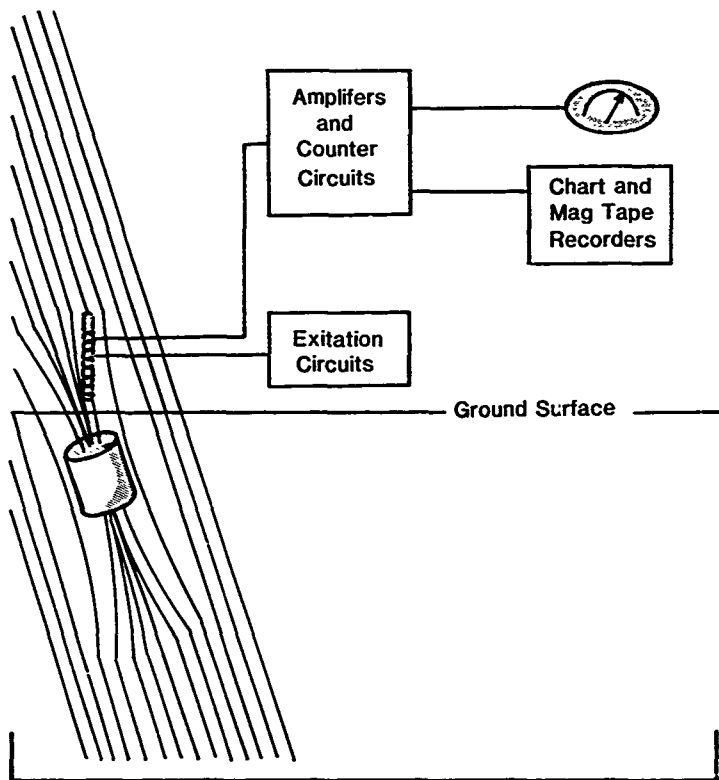


Figure 9. Conceptual Diagram for a Magnetometer (adapted from Reference 21).



electromagnetic energy; thus, it is sensitive to relative dielectric permittivity as well as the electrical conductivity. Whereas the electrical conductivity is more sensitive to the presence of inorganics than organics, the dielectric permittivity is more sensitive to organics than inorganics. Ground penetrating radar has the advantage that depth resolution is controlled by the frequency of measurement and is constant with depth, whereas EM for example, has poorer resolution with increasing depth. Organic materials have relative dielectric permittivities that range from 2 to over 40, according to Reference 36. Adding organics to clay may produce no effect or a large effect, depending on whether or not the two react. As GPR cannot penetrate clay, it cannot see any effect unless the organics coat the clay and destroy the clay-water interaction without adding a new clay-organic reaction. In this latter case, GPR may map clay-organic processes much like complex resistivity. In one example cited, a hydrocarbon plume was detected directly by the GPR as the change in contrast between the dielectric permittivity of sand and water compared to the lack of contrast between sand and oil. In another example, the plume was inferred by an indirect change due to a soil-organic reaction. GPR is most sensitive to changes in dielectric properties in the unsaturated zone down to and at the water table. Below the water table, GPR cannot see changes caused by water-soluble organics directly, but may infer their presence from changes caused by the organics. Of course, GPR is equally effective in mapping geology above or below the water table.

Complex resistivity, sometimes called induced polarization, acquires the same information as the other methods of measuring electrical conductivity, but also measures the frequency dependence of the electrical properties in terms of magnitude and phase (Reference 26). The added information relates to the chemical activity in the earth such as chemical reactions between organic contaminants and clay particles, and directly measures the presence of active chemical processes (Reference 28). Generally, higher phase and nonlinearity (References 28 and 37) indicate greater chemical activity. Inorganic process of oxidation-reduction and of cation exchange may be quantitatively observed with complex resistivity. Organic electrochemistry (Reference 38) suggests a variety of organic processes that may be observable with complex resistivity. To date, only those processes involving reactions between organics and clay minerals have been observed both in the laboratory and at hazardous waste sites. In one example cited, the inhibition of the normal montmorillonite cation exchange process by the organics allowed mapping of the organic plume by complex resistivity (Reference 29).

Since the complex resistivity requires clay to map organics through clay organic reactions, and clay severely restricts the penetration of the ground-penetrating radar, the two techniques are complementary. Further, for hydrogeological information, GPR and seismic methods are complementary because increased clay content in loose and sandy soils improves seismic methods.

## SECTION IV

### FIELD INVESTIGATIONS

#### A. INTRODUCTION

This section presents highlights of the field investigations performed at Holloman AFB, Robins AFB, and Tinker AFB. The highlights focus on results of the performance of soil gas and geophysical measurements for detecting organic contaminants. The results are summarized in Table 5; the more detailed discussions presented in Appendixes A, B, and C are excerpts from the individual site reports. To construct the table, the site of most interest was selected for each base. Methods used to investigate the site were listed along with a brief summary of the result. These results are discussed further below.

#### B. DISCUSSION OF SOIL GAS RESULTS

Comparisons of soil gas and ground water measurements were made at three bases. The site conditions and results of comparisons of soil gas results to ground water data are summarized in Table 6. Although the site conditions included marine sand, clay, mixed sand and clay, and a variety of contaminants, the sites represent a limited set of situations. Because of the wide variety of contaminant and geological conditions possible, the conclusions should be extended to other sites with care. Some of the more generally applicable conclusions are summarized below.

The comparison portion of Table 6 provides the results from active and passive soil gas and ground water sampling conducted at three bases. For each site, soil gas measurements nearest to ground water sampling locations were selected. Distances between the points of comparison ranged from a maximum of 15 meters (50 feet) at Holloman AFB to 6 meters (20 feet) at Robins AFB, and 1.2 meters (4 feet) at Tinker AFB. The values were compared qualitatively by classifying the concentrations as background or above background. The cases for which the classifications of the soil gas and ground water data agreed were counted and presented as a ratio to the total number of cases. For example, at Holloman AFB, active soil gas sampling results agreed with ground water sampling results for 8 of the 12 comparisons. These results are discussed in more detail below.

##### 1. Active Soil Gas Sampling

The active soil gas sampling technique was generally successful at all bases in delineating contamination in the same areas as indicated by the ground water data. Paired soil gas and ground water samples showed agreement at approximately 75 percent of the locations. This percentage might have been improved if the soil gas sampling locations had been closer to the ground water sampling locations. For example at Holloman AFB, the boundary of the contamination was very distinct. In one case when the soil gas and ground water data did not agree, this appeared to be because the well was within the contamination while the soil gas sampling location was not. However, other examples occur when lack of proximity does not explain the disagreement between the results. This also seemed to be true for the other bases. In these cases, the differences are attributed to local inhomogeneities. It is important to rely on the

TABLE 5. KEY RESULTS FROM THE SITE INVESTIGATIONS.

| Base, site, and<br>contaminants                     | Method                                     | Comment   |
|---|--|---|
| Holloman AFB,<br>BX Service<br>Station,<br>Gasoline | Active soil gas sampling                   | Compares favorably with ground water data. Demonstrates movement of contaminants along utility corridors.   |
|   | EM, dc resistivity                         | Do not detect organics because of natural variability in soil resistivity. Culture limited extent of survey.  |
| Robins AFB,<br>JP-4 Spill,<br>. 2-4                 | Active soil gas sampling                   | Compares favorably with ground water data in spite of 20-year age of spill. Demonstrates importance of depth of sampling.                                     |
|   | Passive soil gas sampling                  | Preliminary test has mixed results compared to ground water data.   |
|   | EM, dc resistivity                         | Do not detect organics because of natural variability in soil resistivity due to rainfall effects and culture. Base radar interferes with EM-34 measurements. |
| Tinker AFB,<br>Fuel Farm<br>290, JP-4               | Active soil gas sampling                   | Compares favorably with ground water data; technique effective in clay soil.  |
|   | Passive soil gas sampling                  | Preliminary test has mixed results compared to ground water data. Technique may be responding to surface contamination at times.                              |
|   | EM, dc resistivity,<br>complex resistivity | Were not attempted because of high density of buried pipes and tanks, and fences and pipes on surface.  |

TABLE 6. STUDY SITE AND CONTAMINANT CHARACTERISTICS; COMPARISON OF SOIL GAS AND GROUND WATER DATA.

| Base     | Contaminant | Age (years) | Soil type | Depth to ground water |        | Comparison         |                     |
|----------|-------------|-------------|-----------|-----------------------|--------|--------------------|---------------------|
|          |             |             |           | feet                  | meters | Active agree/total | Passive agree/total |
| Holloman | Gasoline    | 4           | sand/clay | 6                     | 2.0    | 8/12               | not available       |
| Robins   | JP-4        | 20          | sand      | 6                     | 2.0    | 6/8                | 6/9a                |
| Tinker   | JP-4        | unknown     | clay      | 8                     | 2.6    | 9/12               | 5/12                |

These results for Robins AFB use the data for exposure times of 3 days. The 3-day exposure times provided more consistent results than the shorter times of 1 and 2 days.

overall pattern indicated by the active soil gas data, rather than on single values in determining the location of the contamination.

The depth of sampling can be very important, as shown by the results at Robins AFB. At this base, initial sampling at 1 meter revealed very little contamination, as shown in Figure 10, while additional sampling at 2 meters located significant contamination, as shown in Figure 11. It is important to perform depth profiles at a number of locations at the beginning of a study, preferably at several locations known to be contaminated, to select the sampling depth.

The real-time nature of the active soil gas sampling was a significant factor in the success of the investigations at each of the bases. As mentioned above, at Robins AFB it allowed an immediate change to a greater sampling depth when discrepancies were discovered. The availability of results soon after samples were collected offered the opportunity to choose sampling locations and depths based on the best information available.

At Tinker AFB, the active soil gas technique did not appear to be affected by the presence of clay except at a few locations. It was possible to determine when the probe was inserted into impermeable clay by using the value of vacuum necessary to extract a sample as a criterion and adjusting the sampling depth to avoid the impermeable area. In some cases, it was not possible to avoid the impermeable area and the sampling location was changed. The original expectation was that the soil gas technique would not work well in clay. However, in this instance, the active technique performed well, apparently because the permeability of the clay was adequate for soil gas sampling at many locations.

Ground water samples were collected from existing wells at three bases. Additional ground water samples also were collected from soil gas probes. The use of the soil gas probe for collecting ground water samples proved effective

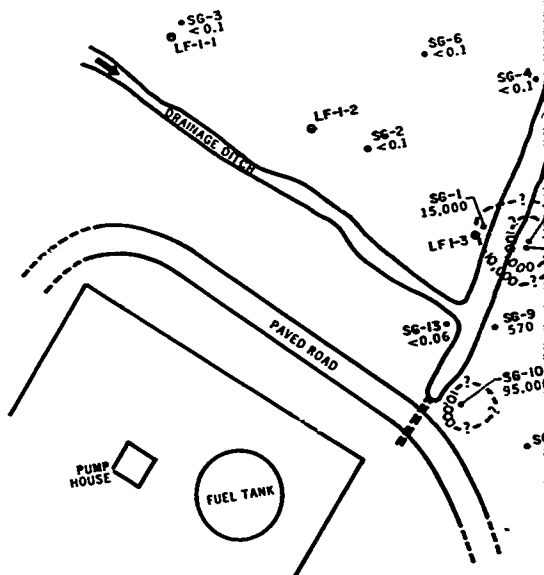
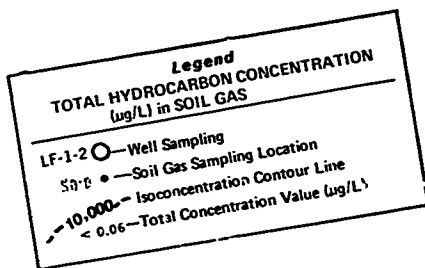


Figure 10. Concentrations of Total Hydrocarbons in Robins AFB. Sampling Depth: 1 Meter.

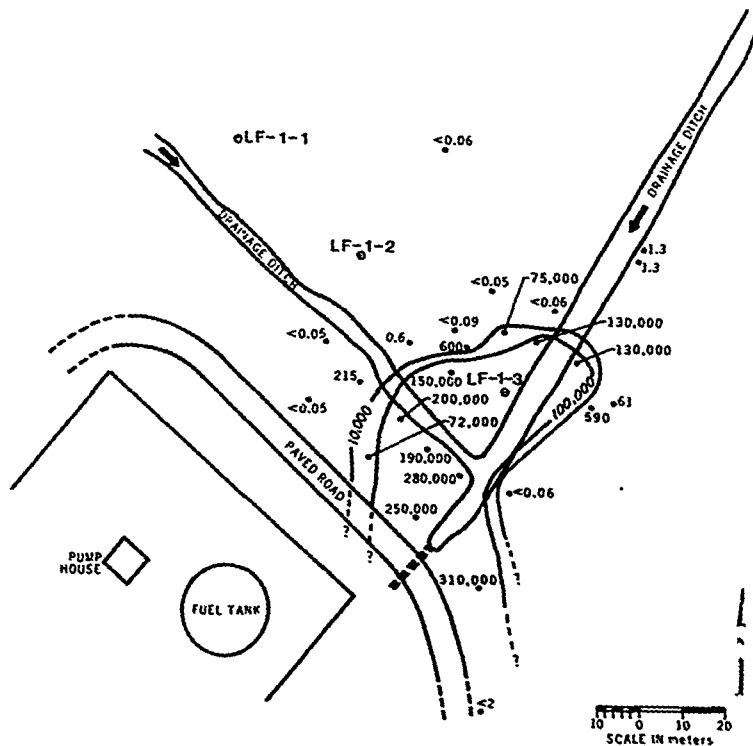
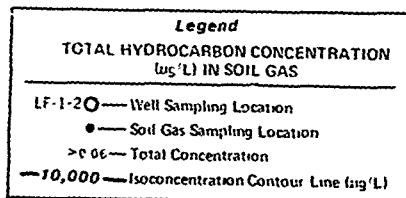


Figure 11. Concentrations of Total Hydrocarbons in Soil Gas at Robins AFB.  
Sampling Depth: 2 Meters.

in timely confirmation of the soil gas results. This approach is not a substitute for the standard procedure of installing and sampling wells, but has its place in field survey activities when delineating the extent of the contamination is the goal. This approach may not work when the soil is very hard, or when the depth to ground water is greater than approximately 3 meters (10 feet).

## 2. Passive Soil Gas Sampling

Two of the sites investigated with active soil gas techniques were also investigated using passive techniques. At these sites, only preliminary tests were performed. The purpose of these tests was to determine the feasibility of mapping the contamination at these sites and to select the best exposure times for the badges. Performing this type test with the badges is very important; an incorrectly chosen exposure time which is too short can indicate an area is uncontaminated when contamination is present. For example, for the exposure times used at Robins AFB, the contaminated zone was successfully identified one out of two times for a 1-day exposure and two out of three times for a 2-day exposure compared to three out of three times for a 3-day exposure. This emphasizes the importance of carefully selecting an exposure time. Overexposure of the badges may result in saturation of the sorbent which would mask any relative differences in soil gas contamination at the various sampling locations.

The passive soil gas sampling badge data showed varying degrees of success in qualitative comparisons with ground water data. For the longest exposure time of 3 days at Robins AFB, the badges successfully indicated one area as contaminated and one area as uncontaminated. These results were consistent with the ground water data. A third area of intermediate contamination was not detected by the badges. The location assumed to have intermediate contamination may have been outside the zone of ground water contamination and influenced by lateral diffusion of VOCs. At Tinker AFB, the badge data matched the ground water data for 5 out of 12 cases. In some of these cases, the badges may have been responding to near-surface contamination, rather than the ground water contamination. These data suggest that the depth of sampling may be as important to passive sampling as it is for active sampling. Overall, the data from passive soil gas sampling with badges showed less agreement with ground water data than the active soil gas method.

The choice of which soil gas technique to choose depends on the nature of the investigation. At this time, a number of questions and issues need further study before the passive soil gas method should be used widely. Because of its lower cost, this technique may be useful for some sites. The issue of greatest concern is understanding the conditions in which the passive badge technique does not detect existing ground water contamination. The use of a preliminary survey to establish exposure times, sampling depths, and gain confidence in the use of this technique at a specific site is essential. Passive samplers generally should be buried at least 0.6 meters (2 feet) below grade to minimize the effects of atmospheric air dilution of soil gases.

As indicated by the results from the various sites, the active soil gas and ground water data show generally good agreement. For this reason, the active soil gas method is recommended for routine use. Depth profiles should be used at the beginning of a study to determine optimum sampling depth. In a

clay environment, consideration should be given to using vacuum values as a criterion for assessing the validity and representative nature of samples. Moisture and organic carbon content of soils can also affect the predictive capability of soil gas techniques even if field sampling can be performed without difficulty.

### C. GEOPHYSICAL RESULTS

A number of limited geophysical studies were conducted for the direct detection of subsurface hydrocarbon contamination. At Tinker AFB, the amount of cultural interference from tanks and pipelines was so great that geophysical surveys were not attempted.

Direct current resistivity and shallow EM surveys were conducted at Holloman and Robins AFBs. These methods were not successful at either base for the direct detection of subsurface hydrocarbon contamination. At Holloman AFB, resistivity anomalies due to the presence of substantial gasoline contamination could not be distinguished from the naturally occurring resistivity variations in the soil of the area. At Robins AFB, where substantial JP-4 contamination was present, no resistivity anomalies in either the dc resistivity or EM results could be distinguished from the natural background resistivity variations in the area. A change in the near-surface resistivity properties due to recent rainfall further tended to complicate and mask any detection. In Reference 39, the resistivity anomalies attributed to the hydrocarbon contamination are represented by decreases in conductivity on the order of 30 to 50 percent from background values. It may be difficult to separate a signal of this magnitude from background variations in many circumstances. For example at Robins AFB, background conductivities were low, approximately 3 to 5 millimhos. The measurements performed did not have the sensitivity to separate relative changes on the order of 1 to 2 millimhos from the background variation.

Based on this experience and the results of two cases reported in the literature (References 39 and 40), the dc resistivity or EM measurements for detection of subsurface hydrocarbons appear to be subtle techniques which depend on a thorough understanding of background information such as near-surface geology and potential interferences, the skill of the instrument operator, and may depend on the length of time the spill has been present. These uncertainties do not preclude the use of these techniques for site characterization to obtain basic information on the electrical resistivity properties of an area.

GPR was not used in the current studies. However, other reports and studies described in Reference 4 indicate that direct detection of subsurface hydrocarbon contamination by GPR surveys has been successful. The use of GPR is limited to sites that are relatively clay-free and that have resistivities greater than about 30 ohm meters. The use of initial reconnaissance EM surveys can help define whether a GPR survey should be attempted at a site. Based upon the results of the present surveys, a GPR survey is recommended as the next phase of investigation at Robins AFB.

When clays are present at a site and the resistivities are less than 30 ohm meters, an emerging technology involving complex resistivity appears to have some potential for the direct detection of subsurface organic contamination (Reference 4). At the present time, further research is needed to fully evaluate the complex resistivity method.



## SECTION V

### GENERAL CONSIDERATIONS FOR SITE INVESTIGATIONS

#### A. INTRODUCTION

This section describes broad and general considerations for a site investigation. The role of a conceptual model and the types of technical concerns which should be considered are addressed. Following these general guidelines, nine examples are presented to illustrate the capabilities of the various techniques; references to actual cases are provided.

The section, except for subsections B, F, K and Table 7, was adapted from materials provided by Dr. John Cherry, a member of the panel of experts listed in Section 11. Subsection B was adapted from materials provided by Dr. Donn L. Marrin, also a member of the panel of experts. Subsection F was adapted from materials provided by Dr. Gary Robbins, another member of the panel. Subsection K was initially developed during discussions by the panel, but is presented in an amplified form which was first documented as Reference 41.

#### B. CATEGORIES OF ORGANIC COMPOUNDS

The type of organic compounds present at a site with subsurface contamination will determine how an investigation is to be conducted and whether the various techniques are likely to be successful. For convenience, the organic contaminants have been categorized into groups which have similar physical properties, i.e., aqueous solubility, density, and Henry's Law constants. The group designations will be used in discussions in this section and in Section VI. Figure 12 shows the vapor pressure and Henry's Law constant for example compounds in each of the groups.

##### Group A: Halogenated Methanes, Ethanes, and Ethenes

These compounds include chloroform, carbon tetrachloride, trichlorofluoromethane (Freon-11), 1,1,1-trichloroethane (TCA), 1,2-dibromoethane (EDS), vinyl chloride, and trichloroethane (TCE). Group A generally represents halogenated organic compounds with vapor pressures greater than 1 kPa and Henry's Law constants greater than  $0.1 \text{ kPa m}^3/\text{mol}$ .

##### Group B: Halogenated Propanes, Propenes, and Benzenes

These compounds include 1,2-dibromo-3-chloropropane (DBCP), 1,2-dichloropropane, 1,3-dichloro-1-propene, chlorobenzene, and trichlorobenzene. Group B generally represents halogenated organic compounds with vapor pressures in the narrow range of 0.1 to 1 kPa.

##### Group C: Halogenated Polycyclic Aromatics

These compounds include polychlorinated biphenyls (PCBs) and organochlorine pesticides such as aldrin, chlordane, heptachlor, and dichlorodiphenyl-trichloroethane (DDT). Group C generally represents compounds with vapor pressures less than 0.1 kPa.

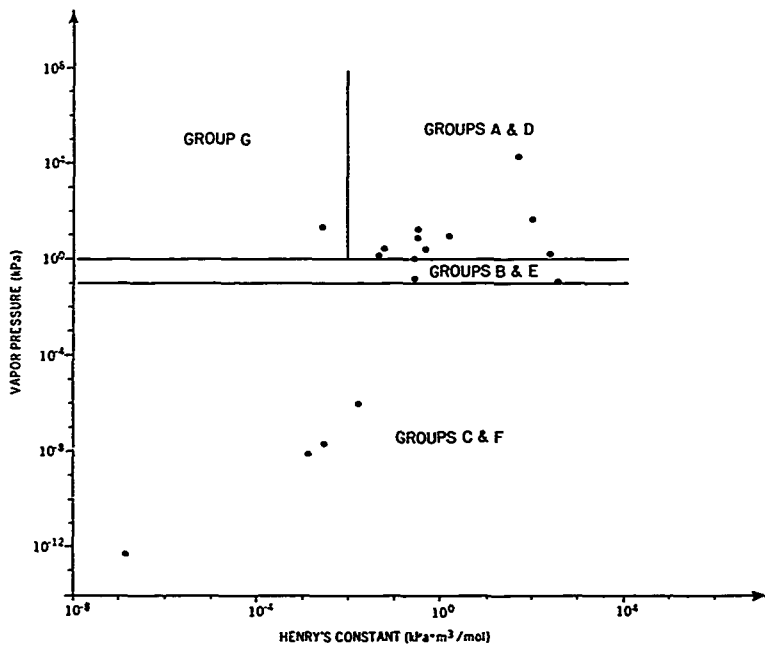


Figure 12. Vapor Pressure and Henry's Law Constant for Example Compounds in Each Group.

#### Group D: C1-C8 Petroleum Hydrocarbons

These compounds include benzene, toluene, xylene isomers, methane, pentane, cyclohexane, isooctane, and complex products such as gasoline and JP-4. Group D generally represents petroleum hydrocarbon compounds with vapor pressures greater than 1 kPa and Henry's Law constants greater than 0.1 kPa m<sup>3</sup>/mol, which is similar to Group A.

#### Group E: C9-C12 Petroleum Hydrocarbons

These compounds include trimethylbenzene, tetramethylbenzene, naphthalene, dimethylnaphthalene, nonane, decane, and complex products such as diesel and Jet A fuels. Group E generally represents long-chain petroleum hydrocarbon compounds with vapor pressures in the narrow range of 0.1 to 1 kPa.

#### Group F: Polycyclic Aromatic Hydrocarbons

These compounds include anthracene, benzopyrene, fluoranthene, benzofluorene, chrysene and complex products such as motor oils and coal tars. Group F generally represents compounds with vapor pressures less than 0.1 kPa.

#### Group G: Low Molecular Weight Oxygenated Compounds

These compounds include acetone, ethanol, formaldehyde, methyl-ethylketone, tetrahydrofuran, and epichlorohydrin. Group G generally represents compounds with vapor pressures greater than 1 kPa and Henry's Law constants less than 0.01 kPa m<sup>3</sup>/mol.

### C. CONCEPTUALIZING THE PROBLEM

The first step in any site investigation is conceptualizing the problem. To do this to a useful degree, some information must be available on the nature of the contaminant source and on the hydrogeology of the site. Useful information on these topics is nearly always available before a site investigation begins, therefore, it is nearly always possible to develop a useful conceptualization before drilling programs and monitoring networks are designed. For the conceptualization, it is desirable to know if the source of contamination has organic floaters or organic sinkers (i.e., halogenated organic liquids) or simply miscible contaminant source liquids. Table 7 lists the density and aqueous solubility of common organic contaminants and classifies those which are insoluble, i.e., have an aqueous solubility of less than 2 percent, and are less dense than water as "floaters" and those which are insoluble and more dense than water as "sinkers." Those which are soluble in water are termed "mixers."

The presence, or possible presence, of organic sinkers is a particularly important issue requiring attention in the conceptualization because the organic liquids can sink deep into aquifers along pathways usually controlled by geologic features. The sinking and final position are rarely influenced much by the rate and direction of ground water flow at the site. If it is known or suspected that halogenated solvents were either used on the site property or disposed of on the site property, a significant mass of the solvent may exist in pockets or pools at some depth beneath the property. The pockets or pools may be the long-term cause of ground water contamination. Depending on the depth at which they are located, the pockets or pools may control the depth and extent of contaminant plumes emanating from the site.

TABLE 7. CLASSIFICATION OF COMMON ORGANIC CONTAMINANTS.

| Name  | Aqueous<br>solubility<br>mg/L | Density<br>g/mL | Classification |
|---|-------------------------------|-----------------|----------------|
| GROUP A   |                               |                 |                |
| Chloroform<br>$\text{CHCl}_3$                                     | 2983 a                        | 1.4832          | sinker         |
| Carbon<br>Tetrachloride<br>$\text{CCl}_4$                         | 146 a                         | 1.5940          | sinker         |
| 1,1,2 Trichloro-<br>ethane, TCA                                   | 4527 a                        | 1.4714          | sinker         |
| Vinyl Chloride<br>$\text{CH}_2=\text{CHCl}$                       | 1100 b                        | 0.9106          |                |
| Trichloroethene<br>TCE, $\text{ClCH}=\text{CCl}_2$                | 1194 a                        | 1.4642          | sinker         |
| Ethylene Dibromide<br>EDB<br>$\text{BrCH}_2\text{CH}_2\text{Br}$  | 3471 a                        | 2.1792          | sinker         |
| Methylene Chloride<br>$\text{CH}_2\text{Cl}_2$                    | 13508 a                       | 1.3266          | sinker         |
| GROUP B   |                               |                 |                |
| Chlorobenzene<br>$\text{C}_6\text{H}_5\text{Cl}$                  | 441 a                         | 1.1058          | sinker         |
| 1,2-Dichloro-<br>propane<br>$\text{CH}_3\text{CHClCH}_2\text{Cl}$ | 2030 a                        | 1.1560          | sinker         |
| 1,3 Dichloro-<br>propene<br>$\text{ClCH}_2\text{CH}=\text{CHCl}$  | insol                         | 1.217           | sinker         |
| 1,2,4-Trichloro-<br>benzene<br>$\text{C}_6\text{H}_3\text{Cl}_3$  | 30 b<br>(25°C)                | 1.4542          | sinker         |

TABLE 7. CLASSIFICATION OF COMMON ORGANIC CONTAMINANTS (CONTINUED).

| Name                                    | Aqueous solubility<br>mg/L | Density<br>g/mL  | Classification |
|---|----------------------------|------------------|----------------|
| GROUP C                                 |                            |                  |                |
| Polychlorinated biphenyls, PCBs         | na                         | na               | na             |
| Dichloro, diphenyl, trichloroethane DDT | .0031 d                    | na               | na             |
| Aldrin                                  | 0.2 e<br>(25°C)            | na               | na             |
| Chlordane                               | 0.056 c<br>(25°C)          | 1.6 c<br>(25°C)  | sinker         |
| Heptachlor                              | insol                      | 1.57             | sinker         |
| GROUP D                                 |                            |                  |                |
| Benzene<br>$C_6H_6$                     | 1800 a                     | 0.87865          | floater        |
| Toluene<br>$C_7H_8$                     | 577 a                      | 0.8669           | floater        |
| Xylene<br>$C_8H_{10}$                   | 186 to 196 a               | 0.8802 to 0.8611 | floater        |
| Methane<br>$CH_4$                       | 24.1 a<br>(25°C)           | 0.5547<br>(0°C)  |                |
| n-Pentane<br>$CH_3(CH_2)_4CH_3$         | 38.5 e<br>(25°C)           | 0.6262           | floater        |
| n-Octane<br>$CH_3(CH_2)_6CH_3$          | 0.66 e<br>(25°C)           | 0.7025           | floater        |
| GROUP E                                 |                            |                  |                |
| 1,2,3-trimethyl benzene<br>$C_9H_{12}$  | 75.2 e                     | 0.8944           | floater        |

TABLE 7. CLASSIFICATION OF COMMON ORGANIC CONTAMINANTS (CONCLUDED).

| Name   | Aqueous solubility<br>mg/L | Density<br>g/mL | Classification |
|--|----------------------------|-----------------|----------------|
| 1,2,4,5-tetra-<br>methyl benzene<br>$C_{10}H_{14}$ | 3.48 e<br>(25°C)           | 0.8875          | floaters       |
| Naphthalene<br>$C_{10}H_8$                         | 38 a                       | 1.4003          | sinker         |
| 1,4-dimethyl-<br>naphthalene<br>$C_{12}H_{12}$     | insol                      | 1.0166          | sinker         |
| Nonane<br>$CH_3(CH_2)_7CH_3$                       | 0.122 e                    | 0.7175          | floaters       |
| Decane<br>$CH_3(CH_2)_8CH_3$                       | 0.952 e                    | 0.7300          | floaters       |
| GROUP F  |                            |                 |                |
| Anthracene   | 0.02 a                     | 1.283           | sinker         |
| Benzopyrene  | 0.0012 e                   | na              |                |
| GROUP G  |                            |                 |                |
| Acetone<br>$CH_3COCH_3$                            | infin c                    | 0.7899          | mixer          |
| Ethanol<br>$C_2H_5OH$                              | infin                      | 0.7893          | mixer          |
| Formaldehyde<br>HCHO                               | solub                      | 0.815           | mixer          |

=====

All information are from Reference 42 and for 20°C unless noted otherwise.

insol = insoluble  
 infin = infinitely soluble  
 na = not available  
 solub = soluble

a. Reference 43  
 b. Reference 44  
 c. Reference 45  
 d. Reference 46  
 e. Reference 47

#### D. CONTAMINANT SOURCE SIZE

Knowledge of the size of the contaminant source provides a basis for deciding on the spacing of monitoring locations. The plume of contamination emanating from a contaminant source which is small in areal extent is normally narrow. Narrow plumes require close lateral spacing of measurement locations for detection or delineation. Although the literature on dispersion contains much controversial and problematic information, there is sufficient data now to conclude that in many aquifers, dispersion in the transverse lateral direction is weak and that plumes often do not spread laterally as they increase in length (Reference 48). In other words, long narrow plumes should be viewed as the rule rather than the exception. This implies that the lateral spacing monitoring wells or other measurement locations must be significantly less than the width of the contaminant source. At some sites, such as those that have a local leak in a liner or those that have had leaks from tanks or hazardous liquid supply lines, the small dimensions at the source present a formidable difficulty. The use of simple models and estimates of longitudinal and transverse dispersivity can be used as an aid to determining suitable monitoring well locations.

The lack of detailed information on the location and size of contaminant sources, as is the case for many sites, presents the greatest obstacle to the efficient development of site investigation plans. To achieve a good probability of detecting zones of ground water contamination at these sites, it is wise to consider soil gas and geophysical techniques for mapping the contamination rather than installing many more monitoring wells or soil sampling holes.

#### E. COMPONENTS OF SITE INVESTIGATIONS

The goal of investigations of sites that are known to be or suspected to be contaminated by organic materials is normally to determine the extent and severity of soil and ground water contamination. Once the extent and severity is known and risks are assessed, plans for any necessary remedial action and long-term ground water monitoring can be developed.

Many investigative techniques are available from which to select those appropriate for the particular site under consideration. Techniques can be selected from the following categories.

- geological
- hydrological
- geochemical
- geophysical
- environmental isotopes
- mathematical models
- soil gas sampling and analytical chemistry

The challenge in any site study is to select the most appropriate combination of techniques for the site-specific nature of the problem. This section will discuss many of these approaches. However, the details of planning soil gas and geophysical investigations will be discussed separately in Sections VI and VII, respectively.

Geological techniques such as drilling and sampling of borehole materials will be included in nearly all site studies because in situ sampling is necessary to confirm the degree and extent of contamination indicated by other techniques.

Hydrological techniques such as the use of monitoring wells for permeability tests and for hydraulic-head monitoring are also an important component of nearly all site studies where organics occur. Permeability measurements and ground water elevation monitoring determine the ground water flow pattern if the geologic framework of the site is also known. Hydraulic head is defined as the sum of three components, the elevation of the point of measurement, or elevation head, the velocity head, and the pressure head. The empirical Darcy's Law describes the flow of a fluid of density  $\rho$  and dynamic viscosity  $\mu$ , such that specific discharge  $v$  is

$$v = -k \rho g / \mu dh/dl \quad (5)$$

and the hydraulic conductivity,  $K$ , is

$$K = k \rho g / \mu \quad (6)$$

where  $k$  is the specific or intrinsic permeability,  $g$  is the acceleration of gravity,  $h$  is the hydraulic head, and  $dh/dl$  is the hydraulic gradient. The permeability  $k$  and the hydraulic conductivity  $K$  are a function only of the medium (Reference 48). Without adequate knowledge of the geology of the sites, determination of the hydraulic head distribution will normally not provide for a good interpretation of the flow net. Most types of monitoring wells can be used for three purposes: permeability tests, head measurements, and acquisition of water samples. Recently, several dedicated monitoring devices that provide ground water samples but are not useful for permeability testing or head monitoring have been developed. Thus, hydrological studies of a site are not necessarily an integral part of the monitoring phase of an investigation.

Geochemical techniques investigate the naturally occurring, generally inorganic chemical processes in ground water. Information about these conditions can prove useful for both site investigations and remedial actions.

In this report, environmental isotopes refer to those isotopes in the ground water that can be used to assist in the determination of ground water age or origin. The isotopes of primary interest are tritium, oxygen-18, deuterium and carbon 14 and 13. Of these, tritium is by far the most useful in studies of sites of organic contamination. In the years 1952 through 1962, tests of large thermonuclear devices were conducted in the atmosphere. This resulted in tritium in precipitation. If a sample of ground water contains high levels of tritium it can usually be assumed that the water entered the ground water zone sometime after 1952. Thus, high concentrations of tritium can be used to identify ground water less than 35 years old (Reference 48).



Mathematical models have a potential to aid in the interpretation of hydrology and contaminant transport. Such models offer a formal means of displaying or assessing conceptualizations of the conditions at the site. Mathematical models are rarely a means of reducing much of the need for site data, but they do offer possibilities for making better use of the data that are obtained. Ground water flow models often serve a useful and often essential component in site studies. However, solute transport models that include the combined effects of advection, dispersion and retardation are rarely essential to a site investigation, although they are useful for risk assessment and design of remedial actions.

In the development of a strategy for an investigation of organic contamination at a site, all of the various investigative techniques or tools should be considered for selection of those particular items that may be useful. The planned investigation should be formulated in several phases. The phases should generally be sequential in the earliest stages. The approach should allow for extensive feedback as phases are completed so the new information can be applied to improve the investigation strategy.

#### F. PRELIMINARY INFORMATION

Before beginning a study, information in a number of categories is essential to aid in the choice of monitoring techniques, the design of survey grids the procedures for using the instruments, and the interpretation of the data. As mentioned earlier, this list was compiled with the assistance of Dr. Gary Robbins, a member of the panel of experts listed in Section II. The categories listed have been divided into broad groups: hydrogeology; soil, surficial geology, and bedrock; site layout; and contaminant source information. Sources for this information include local consulting engineers, county offices, state geological and water surveys, U.S. Geological Survey reports and maps (Reference 49), the National Climatic Center, the Soil Conservation Service, and construction and foundation reports for structures on site. The information described in the list will be helpful in choosing techniques and planning survey grids. Without this information, there will probably be a need for application of additional techniques to provide confidence that the contamination has been detected successfully and completely.

##### 1. Hydrogeology

###### a. Existing wells

- (1) Locations
- (2) Uses, past and present
- (3) Quality of ground water, presence of contamination, for different aquifers
- (4) Well logs and driller's logs
- (5) Screened intervals
- (6) Pumping rates, specific capacity, transmissivity, hydraulic conductivity, cones of depression, storage coefficients

###### b. Elevation of the water table

- (1) Regional and on site
- (2) Seasonal fluctuations, if available

- c. Thickness and distribution of aquifers and aquitards; existence of perched aquifers
  - d. Ground water flow velocity or gradient, both local and regional
  - e. Soil porosity, moisture, and lithology
  - f. Recharge and discharge areas
  - g. basic climatic information, including annual precipitation, and monthly temperatures
  - h. Nature of drainage conditions, and flooding
2. Soil, Surface Geology, and Bedrock
- a. Types, thickness, and lateral distribution of strata
  - b. Properties of soil including color, density, porosity, infiltration rates, hydraulic conductivity, soil suction relations, grain size distribution, Unified Soil Classification System (USCS) classification, moisture content, soil chemistry, and organic content
  - c. Type and extent of fill if present
  - d. Boring logs for nearby construction
  - e. Stratigraphy and lithology (particularly noting the presence of clay)
  - f. Location and Type of Bedrock
    - (1) Mass properties (faulting, fracturing, layering, dips, and strikes)
    - (2) Geologic maps
    - (3) Regional geology
    - (4) Regional gravity and magnetic data
    - (5) Depth
3. Site Layout
- a. Historical and current aerial photographs
  - b. Present and past use of site
  - c. Topography and nature of surface, in terms of woods, vegetation, bare soil, outcrops
  - d. Location of buildings, other facilities such as runways, and survey markers
  - e. Nature and location of roads for access

- f. Nature and location of pipelines, utilities, and underground facilities which may be conduits for contamination, obstacles to investigation activities, or both
  - g. Location of power, water, and lighting which may be needed in investigation activities
  - h. Nature of pavement including type, thickness, and reinforcement
  - i. Nature of activities on site which may influence subsurface conditions, such as irrigation, or pumping wells
  - j. Nature and location of safety hazards
4. Contaminant Source Information
- a. Identity of organic contaminants
  - b. Locations of spills and leaks (tanks, sumps, dumps, pipelines, impoundments, etc.)
  - c. Amounts spilled or leaked; past problems of similar nature
  - d. Time or duration of events
  - e. How problem was discovered
  - f. Depth of contamination
  - g. Characteristics of problem such as odors, seepage, or a contaminated well
  - h. Actions to clean up problem
  - i. Contamination due to other sources, including chemicals, concentrations extent of problem, time frame of problem, remedial actions being performed
5. Status of Early Knowledge

In any site investigation for contaminant migration, determination of the geological conditions is a key task. A good monitoring strategy cannot be developed until a considerable amount of information is obtained on the geology of the site. If very little is known about the geology of the site before the investigation begins, then an important early step in the investigation should be a preliminary geological investigation.

#### 6. The Zone of Relevance

In most site studies, it is usually determined that there is a depth controlled primarily by geological conditions below which contaminants have not penetrated. The entire zone above this depth can be referred to as the zone of relevance. For example, if the site is situated on an unconfined sand aquifer with an aquitard of clay, the sand would constitute the zone of relevance. It

is obvious that the site study should focus primarily on the zone of relevance. But to determine where the bottom of the zone of relevance is located, a component of the site study must extend beneath the bottom of the zone. If the bottom of the zone of relevance can be located early in the site study, the remainder of the study can proceed with greater efficiency. Often, drilling to determine the geological conditions provides appropriate information to draw a tentative conclusion regarding the bottom of this zone. This conclusion can then be assessed by other means such as ground water monitoring.

#### G. GEOLOGICAL TECHNIQUES AND ISSUES

When selecting the geological techniques of drilling and coring for a site investigation, many questions should be addressed. The following list of questions may be useful to consider. The order of the questions is not significant.

- What type(s) of drill rig(s) should be used?
- Can the use of drilling mud or other drilling additives be avoided and, if so, how?
- What type of soil or rock sampling methods should be used?
- What soil or rock sampling interval should be selected?
- How should the soil or rock samples be stored?
- Should an organic vapor analyzer be used in the field to screen the soil and rock samples?
- To what depth should the boreholes be drilled?
- Should the boreholes be used for installation of monitoring wells or should they be plugged?
- What techniques should be used to plug the holes?
- If it is expected that fractures are the main route for contaminant migration, should angle boreholes be drilled as well as vertical holes?
- Has a geologist with specific knowledge or experience pertaining to the local geology been consulted in the development of the preliminary geological interpretation of the site?
- To what depth is it reasonable to expect root holes, animal burrows and desiccation cracks to penetrate from the ground surface?
- When boreholes are drilled and sampled, to what depth are weathering features identifiable?
- If it is known or suspected that dense immiscible liquids have been used/spilled/buried at the site, what geological contact or layer would most likely have acted as a barrier to the sinking of the liquid?

- If possible geological barrier beds or contacts can be identified, what is the dip of the surface along which dense immiscible liquids might move?
- What procedures should be used to prevent further spread of contamination if this barrier is penetrated?

#### H. HYDROLOGICAL TECHNIQUES AND ISSUES

When selecting hydrological techniques for a site investigation, many questions should be addressed. The following questions can help to better define the important decisions to be made for a given site investigation:

- Can the available geological knowledge of the site and the general hydrological setting be used to develop a preliminary estimate of the ground water flow pattern?
- Is the depth to the water table relevant information? How should it be determined?
- Should a network of monitoring wells be used to determine the ground water flow pattern?
- What techniques would be best for determination of ground water velocity?
- What type of aquifer test should be used?
- Is there a need to use pumping tests to establish the degree of hydraulic connection between one part of the site and some other part?
- Are there aquitards at the site and if so, do they act as barriers to contaminant migration?
- Should laboratory permeameter tests be done on core samples?
- If fractured clayey deposits occur at the site, has drilling caused smearing of the fractures in the borehole, thereby changing the hydraulic properties?
- Are the ground water flow conditions observed now at the site the same as those that existed when ground water contamination began to occur?
- If contaminant migration is occurring at the site, does it occur by porous media transport or fractured media transport?
- If it is expected that the fractured media transport of contaminants occurs, how can estimates of the bulk fracture porosity be obtained for velocity estimates?
- If the mode of flow and transport is via fractures, what is the porosity of the blocks between the fractures?
- At what depths or in what zones do the critical solute-transport paths occur?

- Should detailed vertical profiles of hydraulic head be obtained to assist in the identification of depths of critical flow paths?
- How much annual infiltration is expected to occur at the site?
- In the zone in which contaminant migration is most likely to occur, what is the degree of heterogeneity and what dispersion tendencies are expected?
- What are the locations and yields of water supply wells in the area?
- How does the potentiometric surface respond to precipitation and what does this indicate with respect to the ground water flow system?
- Is the geology of the site suitable for use of multilevel monitoring devices in single boreholes or is it necessary to drill many holes to different depths at each location in order to do monitoring at many depths?

#### I. GEOCHEMICAL TECHNIQUES AND ISSUES

When selecting geochemical techniques for a site investigation, numerous questions should be addressed.

- What are the redox conditions in the ground water zone and is it likely that these conditions will affect transformations or degradation of organic contaminants?
- What is the weight percent of solid phase organic carbon in the geologic materials and what degree of contaminant retardation would it be expected to cause?
- Is there evidence of transformations (i.e., biodegradation, hydrolysis)?
- If the geological media allow contaminant transport via fractures, what will be the influence of the matrix diffusion effect?
- Can inorganic parameters such as major ions or electrical conductance be used as indicators of transport paths or contamination?
- Would it be useful to measure parameters such as pH, Eh,  $\text{CH}_4$ , hardness, alkalinity, and dissolved oxygen when sampling monitoring wells?
- Do samples of water from monitoring wells contain  $\text{H}_2\text{S}$  and if so, what does this mean?
- Are there clay-rich aquitards at the site and are they such that molecular diffusion is the dominant influence on solute transport?
- Do core samples from the geologic deposits show evidence of chemical weathering and if so, what does this indicate regarding the development of fractures?
- Should diffusion coefficient measurements be made on core samples?

## J. ISOTOPIC TECHNIQUES AND ISSUES

The presence of tritium can be used to help define the zone of relevance. If the contamination has occurred more recently than 1953, then the presence of tritium may be a useful indicator of the possible extent of the hydrocarbons. However, if organic chemicals which are more dense than water have been used at the site, then tritium is generally not a good indicator of the expected zone of contamination. This is because contaminants which are more dense than water can sink through the aquifer into zones much deeper than tritium moves under the influence of ground water flow alone (References 48, 50, 51). Tritium analyses are available commercially from the University of Miami Tritium Laboratory.

When selecting isotopic techniques for site investigation, several questions should be addressed. These are listed below. The order of the questions is not significant.

- Is it likely that the site became contaminated after 1953 and if so, should bomb tritium be used as an indicator of the zone of active ground water movement that is susceptible to post-1953 contamination?
- Is there evidence that organic contamination exists in ground water samples that have no bomb tritium?
- If it appears appropriate to use bomb tritium in the site investigation, what detection limit and precision is appropriate to request in the tritium analyses?
- Should tritium profiling be used to determine whether or not an aquitard beneath the site is leaky?
- Should water samples for tritium analysis be acquired from monitoring wells or by extraction of water from cores?
- Can the mapping of tritium in ground water at the site serve as a means of delineating the zone of relevance for site monitoring?
- Is it likely that organics as dense immiscible liquids have travelled in a manner that would mean that bomb tritium is not a good travel-path or travel-time indicator?
- Is it likely that isotopes in addition to or other than tritium can play a useful role in the site study?
- If the contamination is known to have or suspected to have originated from a lagoon or pond, is it likely that oxygen-18 and deuterium will serve as an indicator of the source water?

## K. LITERATURE REVIEW

Numerous studies of subsurface organic contamination have been conducted and reported in the literature. This discussion provides a series of examples of contaminant and geology combinations along with references to studies of that type in the literature. Each of the cases is meant to represent a broad

category of contaminated sites and to serve as an aid to visualizing the distribution of the contamination. This will make it easier to plan the investigation. A brief discussion of indirect monitoring techniques which may be appropriate for each case also is provided. These conceptual drawings were developed and techniques were selected during the 2-day meeting of the panel of experts.

The characteristics of the cases include sand and gravel, clay, fractured bedrock, and karst limestone; shallow and deep aquifers; and fuel, solvents and landfill leachate. Actual site conditions usually would be more complex than these hypothetical cases (Reference 52), but complexity alone would not dictate a different choice of techniques. Instead, complexity will increase the number of techniques necessary for complete understanding of the contaminant location.

Nine hypothetical cases have been developed to represent common combinations of sources, contaminants, and hydrogeology. The hydrogeological medium for six of the nine cases is sand and gravel. Clay was assumed to be present in the sand and gravel, but at low enough proportion to not affect the organic contaminant migration. The remaining three cases deal with the complexities of clay, crystalline fractured rock, and karst terrain.

#### 1. Fuel Leak Over Unconsolidated Sand and Gravel Aquifer

In this example shown in Figure 13, gasoline or other non alcohol fuel has leaked from some surface or near-surface source, continuously or frequently for several years. The fuel, which is of lower density than water, floats on top of the water table. Some fuel is trapped in the unsaturated zone as coatings on soil particles; and some constituents dissolve in the ground water, while others volatilize and diffuse away from the fuel pool. The horizontal transport distance will depend on the volume of the leak, ground water velocity, and other parameters. Soil gas techniques are likely to be successful in this situation and are the techniques of choice. If the resistivity of the soil is greater than 30 ohm meters, GPR may be useful for providing additional detail about the extent and contamination present. For a discussion of an actual example with attendant complexities, Reference 53 describes an investigation of a crude oil leak at Bemidji, Minnesota. Reference 10 describes a gasoline leak over a sand and gravel aquifer. Indirect mapping of a fuel plume by EM induction is described in Reference 54; a conductive plume was present which was thought to be ferrous iron which dissolved in ground water under the anaerobic (reducing) conditions caused by fuel biodegradation.

#### 2. Solvent Leak Over Sand and Gravel Aquifer

This case, shown in Figure 14, is similar to Case 1 except that trichloroethylene and other common chlorinated solvents are denser than water and sink through the unconfined aquifer until an aquitard is reached. The solvent may pool in depressions on the aquitard. Each pool of solvent then acts as a secondary source contaminating the ground water, possibly for many years after the surface source is removed. When performing the investigation, the aquitard should not be penetrated unless appropriate drilling precautions are applied. The well should not provide a conduit for the solvent to contaminate lower aquifers. As in the previous case, soil gas techniques are expected to be successful and GPR may be useful, if the resistivity of the soil is greater than 30 ohm meters. For an extensive discussion of an actual case in Pensacola, Florida, where the investigation of creosote contamination, including phenols,



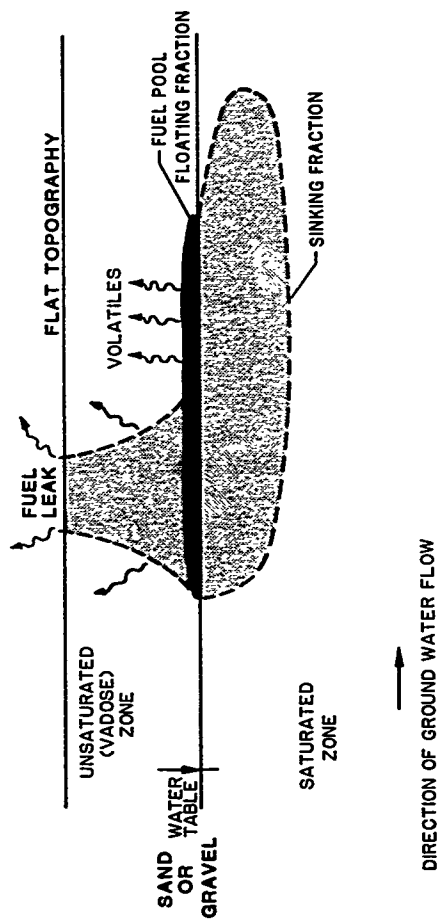


Figure 13. Fuel Leak Over Unconsolidated Sand and Gravel Aquifer.

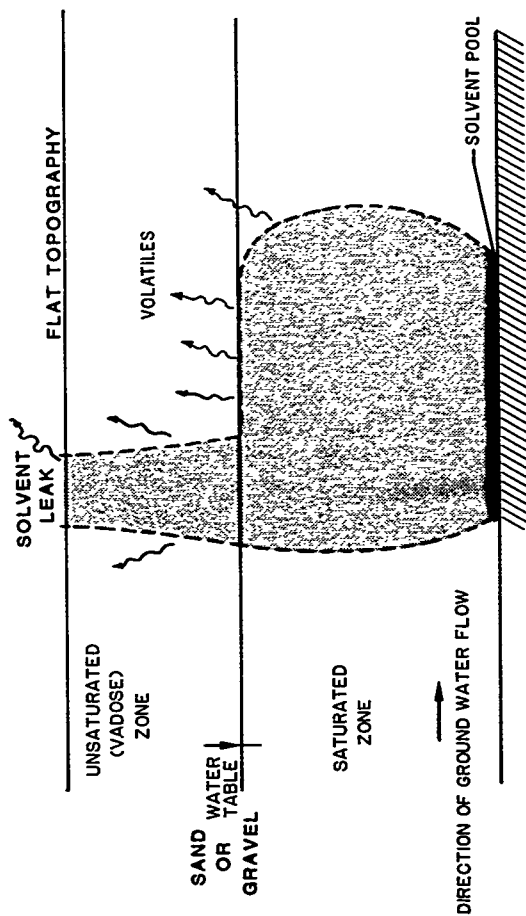


Figure 14. Solvent Leak Over Sand and Gravel Aquifer.

was complicated by the presence of clay lenses, see Reference 55. References 56 and 57 discuss an investigation of soil gas above TCE-contaminated ground water. Reference 58 describes a site with a soil consisting of a mixture of sand, gravel, and clay, and chlorobenzene and benzene contamination in ground water at Pittman, Nevada.

### 3. Landfill Over Unconsolidated Sand and Gravel Aquifer

A landfill, shown in Figure 15, is a much larger area source than most fuel and solvent spills, usually covering acres of land. The permeability of landfills is usually higher than the surrounding soil; and this leads to ground water mounding beneath the landfill after rainfall. Such a mound is a dome in the topography of the water table, whose height and permanence depends on the frequency and intensity of rainfall. Landfills usually leach organic and inorganic contaminants. The inorganic contaminants may be roughly collocated with the organic contaminants, although the two contaminant types migrate at different speeds. In this case, the inorganic plume may be useful for locating the organic contamination. Landfills generally produce gases which can vary in composition according to the age of the fill. These constituents include nitrogen and hydrogen, which may be released for brief periods of about 2 to 3 months and carbon dioxide and methane which may be released for several years after the placement of fill. Soil gas sampling for carbon dioxide, methane, or VOCs may be useful for locating the contamination. If the depth to the aquifer is less than 8 meters, and a conductive ground water plume is present, EM, resistivity, or GPR may be useful for detecting the inorganic contamination. Measurements using EM, GPR, and magnetics on top of the landfill can locate the presence of metal trash. Reference 59 describes an actual case at Borden landfill in Ontario, Canada. Reference 60 describes the effect of a landfill on the hydrogeologic environment.

### 4. Sewage Leach Field Over Unconsolidated Sand and Gravel Aquifer

A centralized sewage leach field, shown in Figure 16, typically covers a large area, which is similar to a landfill. The sewage water causes a ground water mound beneath the sewage leach field. The concentrations and presence of the organic contaminants will be variable because some of the sewage is biodegradable. If the water table is less than 30 meters (100 feet) in depth, the EM and resistivity techniques may detect a conductivity increase caused by the presence of inorganic constituents such as ammonia and nitrates. Soil gas sampling for methane may be ineffective if soil moisture beneath the leach field reduces the effective porosity to less than 5 percent (Reference 57). Seismic techniques can be considered for determining the depth of the water table when it is greater than 30 meters. Reference 61 describes the investigation of such a case at Cape Cod, Massachusetts.

### 5. Leak Over Deep Aquifer

In this case shown in Figure 17, because of the volume of the leak or the depth to the aquifer, there is reason to suspect that the fuel, solvent or landfill leachate has not reached the water table. Other reasons this may occur include biodegradation, volatilization, sorption onto clay and soil particle surfaces, impermeable layers of clay, moisture barriers, or low infiltration rates. The leak will descend in a narrow, vertical column unless clay lenses or variations in permeability redirect the flow. Analysis of soil

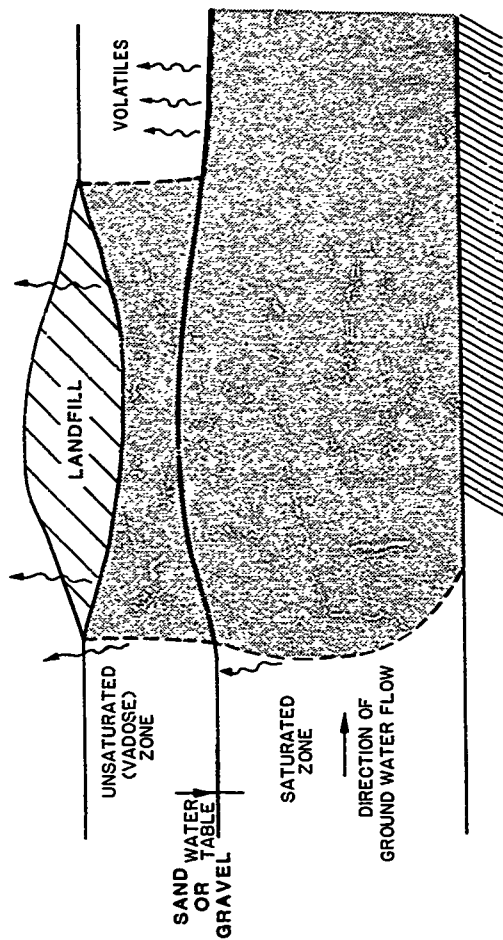


Figure 15. Landfill Over Unconsolidated Sand and Gravel Aquifer.

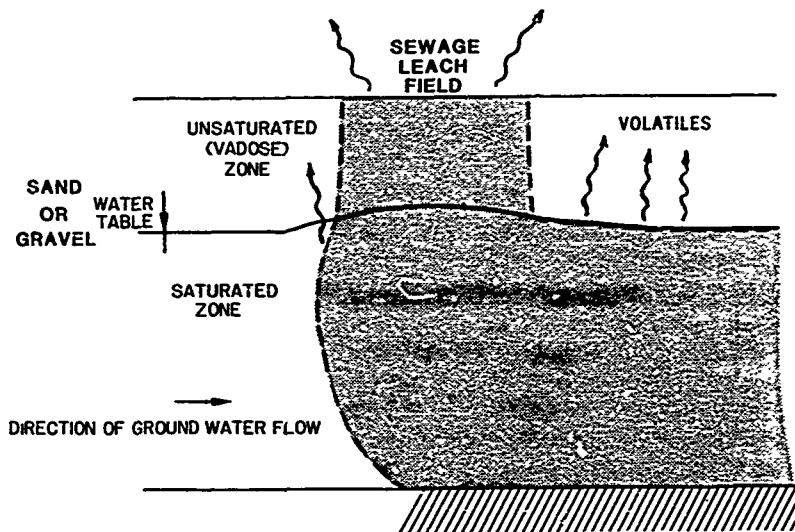


Figure .6. Sewage Leach Field Over Unconsolidated Sand and Gravel Aquifer.

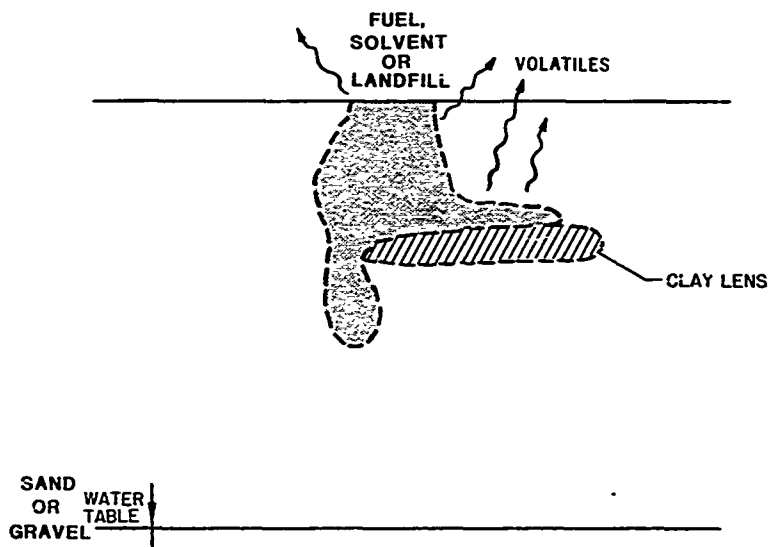


Figure 17. Leak Over Deep Aquifer.

gas near the source can determine the lateral diffusion of the volatile organic contaminants. Core sampling can establish the vertical extent and actual concentration of the contaminant. When performing the investigation, care should be used to avoid breaching confining layers, thereby allowing new migration paths for the contaminant. This case is similar to a study of contamination in the unsaturated zone from low-level radioactive hospital waste containing organic solvents and carriers (References 62 and 63).

#### 6. Fuel and Solvent Leak Over Two Interconnected Aquifers.

This case shown in Figure 18, provides more structural complexity. Fuel will float on top of the unconfined aquifer, while the solvent will form pools on top of both aquitards. Some solvents will dissolve in the fuel, and some fuel components will dissolve in the solvent. The ground water may flow in different directions in the two aquifers. Therefore, detecting the plume in the unconfined aquifer does not locate the plume in the confined aquifer. The silt/clay aquitard between the aquifers acts as a barrier to the upward migration of organic vapors and to the penetration below the unconfined aquifer of electrical current as might be used in a geophysical survey. Resistivity can provide information on the hydrogeology, possibly identifying the depth of the water table and both aquitards. Resistivity is more likely to determine the complex structure than is EM. Seismic techniques can also be used to help determine these depths. Soil gas techniques can map the contamination in the upper aquifer. The drilling of monitoring wells must proceed carefully. The aquitards should not be penetrated unless appropriate drilling precautions are applied. The drilling should not provide a conduit for the contaminants to move between aquifers, yet it is the only method to obtain information for the lower aquifer. An actual example of a case with multiple aquifers is the St. Louis Park study (Reference 64).

#### 7. Fuel Leak Over Crystalline Fractured Rock

This case shown in Figure 19, illustrates the complexity of contaminant migration where the presence and orientation of the fractures dictates the pathways followed by the organic contaminants. Aerial image analysis can find major fractures or fracture patterns; field mapping should be used to check these results. This information may suggest where to install wells. GPR, with its continuous profiling capability, may locate fractures if the resistivity of the rock is less than 30 ohm meters. Otherwise, seismic or resistivity techniques should be used. Resistivities for many rock types are given in Reference 18. Soil gas sampling at locations of fractures indicated by the earlier techniques can be used to develop further information regarding the presence and type of contamination in the fractures. Monitoring wells may have to be angled to intercept the fracture pathways. Reference 65 evaluates methods for measuring hydrological variables in fractured rock units. Examples of geological characterization of waste sites located over fractured rock include References 66-68.

#### 8. Fuel Leak Over Thick, Fissured Clay

In this case, shown in Figure 20, the leaked fuel travels along unknown pathways through the clay to the top of the water table. The fuel forms a pool at the water table and the fuel constituents dissolve from that pool into the ground water and travel downgradient. As in the case above, the pathway is unknown. Clay has a high electrical conductivity and it is difficult for the

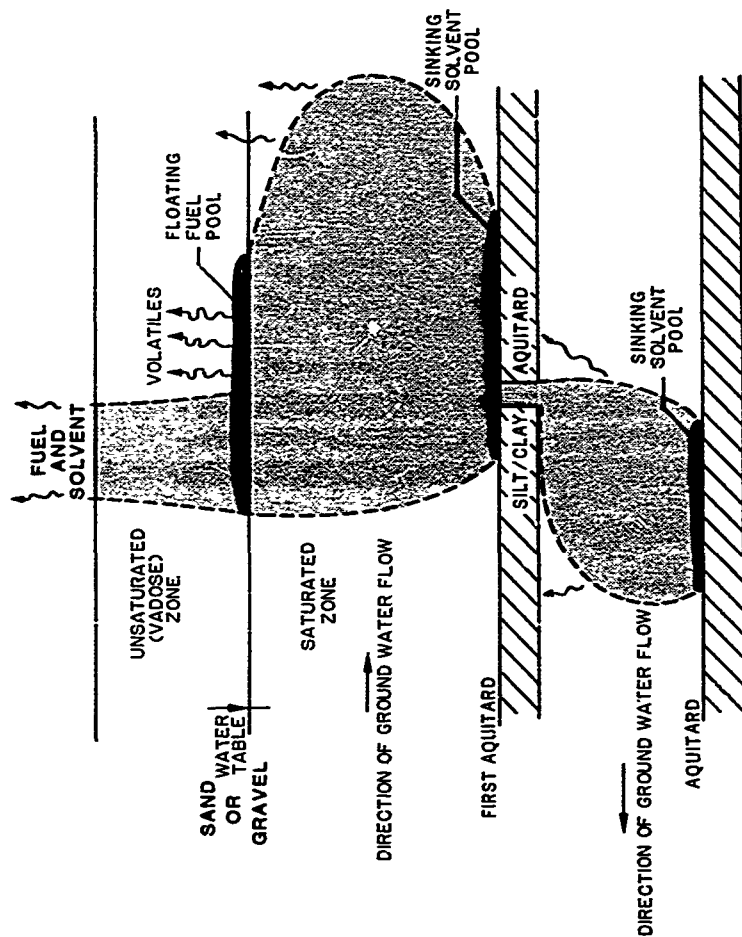


Figure 18. Fuel and Solvent Leak Over Two Interconnected Aquifers.



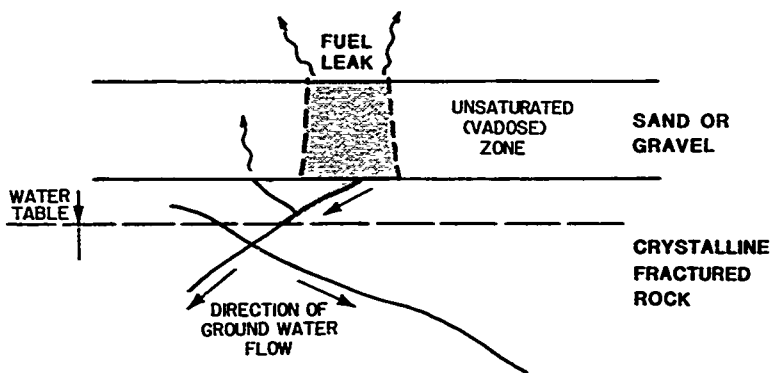


Figure 19. Fuel Leak Over Crystalline Fractured Rock.

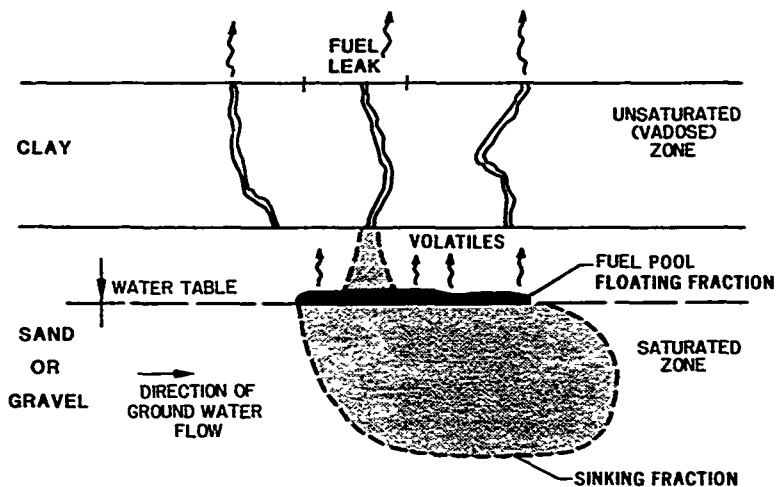


Figure 20. Fuel Leak Over Thick, Fissured Clay.

electromagnetic energy of a current field to penetrate. The clay is also a barrier to the upward diffusion of VOCs. Clay layers at any depth above the first aquitard have the same effect. Monitoring wells and soil cores have the highest likelihood of success. It may be worthwhile to have an experienced geophysicist apply the complex resistivity technique. Reference 69 describes a hydrogeological investigation for a site with fractured shale.

#### 9. Fuel Leak Over Karst Terrain

Karst terrain usually contains a network of complex fractures, channels, caves, and underground streams which are the migration pathways for contaminants, as shown in Figure 21. As in the crystalline fractured rock example, aerial image analysis can be used to find major features of the karst network with field mapping to check the results. Tracers are one of the best methods to determine flow paths. This information may suggest where to install wells. Ground-penetrating radar can be used to locate fractures if the resistivity of the rock is greater than 30 ohm meters. Its capability of continuous profiling is particularly useful in this case. Direct current resistivity should be used instead of GPR if the apparent resistivity of the soil is less than 30 ohm meters. Seismic techniques should be used along with both of these electrical methods to obtain independent information on the location of major geologic features of the karst terrain. Sampling and analysis of soil gas at channel openings can indicate the presence and type of contamination. Monitoring wells may be placed using the results of the surveys. The monitoring wells may have to be angled to find the channels. A description of a site investigation in karst terrain is given by Reference 70.

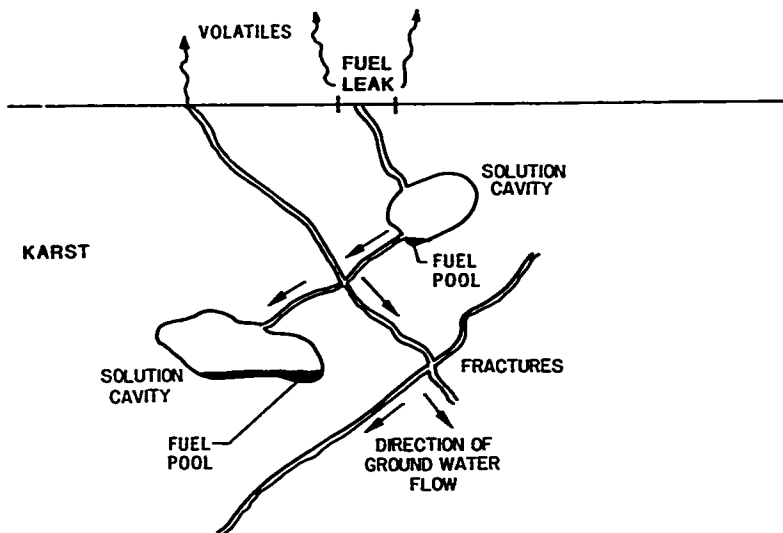


Figure 21. Fuel Leak Over Karst Terrain.

## SECTION VI

### PLANNING A SOIL GAS INVESTIGATION

#### A. INTRODUCTION

This section was adapted from materials provided by Dr. Donn Marrin, a member of the panel of experts listed in Section II. The purpose of this section is to identify the types of subsurface contaminant problems which are amenable to soil gas sampling. Furthermore, it is designed to illustrate environmental conditions under which soil gas sampling is either not appropriate or subject to misleading interpretations. Soil gas investigations must be designed and interpreted according to the hydrologic/geologic setting and chemicals which are present at each site. A variety of investigative and interpretive techniques may be used at a single site if there are variable environmental conditions or multiple objectives to fulfill.

As discussed in Section III, active soil gas sampling methods are recommended until the passive method is better understood. While the active method costs more per sample, the convenience of real-time analysis may allow for less samples overall, if the objective is to delineate a plume. The active method has proven reliable not only in the Air Force studies, but also in many other studies. In comparison, the passive soil gas sampling method costs less per sample, but more samples may be needed because analysis is not real-time. In addition, the passive method may be prone to false negatives. For these reasons, the discussions below are directed to active soil gas sampling approaches although much of the information is also applicable to passive sampling techniques.

The section is organized into six parts. The first two parts evaluate the likelihood that a specific contaminant can be detected in soil gas, from both general and compound-specific view points. Successful detection of a contaminant in soil gas depends not only on the properties of the contaminant, but also on the geology, hydrology, and study objectives, which are specific to a site. The remaining three parts discuss sampling approaches and formulation of an investigative plan, interpretation of results, and when not to use soil gas methods.

#### B. GENERAL CONSIDERATIONS

There are no absolute limits for VOC concentrations in soil or ground water below which soil gas sampling is ineffective. The lower limit is a function of: (1) contaminant properties, (2) analytical detection limits, (3) physical states and depths of the contaminant, (4) hydrologic and geologic conditions, and (5) interference from surface or subsurface sources and degradation processes. Except for analytical detection limits which were discussed in Section V, and degradation processes which are part of topic (5), the remaining topics are discussed in detail below. The role of degradation processes is discussed with the contaminant specific information. Soil gas investigations are commonly performed as screening or initial assessment procedures where few of the site-specific questions can be answered. Soil gas sampling can be conducted with a minimal amount of background information. However, the results will generally be more difficult to interpret.

## 1. Physical Properties of Contaminants

Some knowledge about the contaminants present is essential to evaluating the feasibility of a soil gas investigation. Likely contaminants can be classified into the groups such as those designated in Section V. If contaminants are not listed, their physical properties can be obtained from a variety of chemical references. Vapor pressures less than  $10^{-6}$  kPa are considered very low; vapor pressures in the range of  $10^{-6}$  to  $10^{-1}$  kPa are considered low; vapor pressures in the range of 0.1 to 1 kPa are considered moderate; and vapor pressures greater than 1 kPa are considered high. Generally, soil gas sampling is most effective for compounds with vapor pressures above 1.0 kPa and Henry's Law constants above 0.1 to 0.5 kPa m<sup>3</sup>/mol. If vapor pressures and Henry's Law constants are not available, then compounds with boiling points below 125°C can probably be detected in soil gas (Reference 61). This information is summarized for common ground water contaminants in Table 8.

Henry's Law constants are a measure of air-water partitioning at equilibrium. Henry's Law constants can be estimated from a compound's vapor pressure, aqueous solubility and molecular weight according to Equation (7).

$$H = \frac{VP}{S} \quad (7)$$

where:

$$H = \text{Henry's Law Constant} \quad \frac{\text{kPa} \cdot \text{m}^3}{\text{mol}};$$

V = vapor pressure (kPa):

$$M = \text{gram molecular weight} \quad \frac{\text{g}}{\text{mol}}; \text{ and}$$

$$S = \text{aqueous solubility} \quad \frac{\text{mg}}{\text{L}} \text{ or } \frac{\text{g}}{\text{m}^3}.$$

Vapor pressure and aqueous solubility values must be determined for the appropriate environmental temperatures.

## 2. Physical States and Depths of Contaminants

Compounds may exist in the subsurface in several physical states including: (1) dissolved in water, (2) dissolved in another organic phase, (3) adsorbed on soil materials, (4) pure liquid in either the saturated or unsaturated zone, and (5) present only in the gas phase. The physical state is rarely determined directly but can be estimated on the basis of compound properties, disposal practices, and subsurface conditions. The physical state of a compound determines the degree of phase partitioning, if any, which must occur to permit gas-phase analysis of subsurface contaminants.

In many cases, contaminants have densities greater than 1.0 gram/mL and will sink as immiscible liquids in aquifers. It is possible for floating hydrocarbon products to act as a solvent for high-density compounds (e.g. halogenated

TABLE R. USEFUL DATA FOR SELECTED ORGANIC CONTAMINANTS.

| Name  | Group | Boiling point °C | Vapor pressure kPa <sup>a</sup> | Molecular weight | Aqueous solubility mg/L <sup>a</sup> | Henry's Law constant kPa m <sup>3</sup> /mol <sup>a</sup> | References    |
|---|-------|------------------|---------------------------------|------------------|--------------------------------------|---|---------------|
| Chloroform<br>CHCl <sub>3</sub>                 | A     | 61.2             | 21.33                           | 119.378          | 2983                                 | 0.336   | f, c, f, b, b |
| Carbon<br>Tetrachloride<br>CCl <sub>4</sub>     | A     | 76.6             | 12.17                           | 153.823          | 146                                  | 2.35  | f, c, f, b, b |
| 1,1,2-Trichloroethane<br>TCA                    | A     | 74.0             | 3.30                            | 133.41           | 4527                                 | 0.075   | f, g, f, b, b |
| Ethylene Dibromide<br>EDB                       | A     | 131.0            | 1.5                             | 185.85           | 3471                                 | 0.0618  | d, d, f, b, b |
| Chlorobenzene                                   | B     | 131.7            | 1.17                            | 112.589          | 441                                  | 0.346   | f, c, f, b, b |
| Dichloro, diphenyl, C<br>trichloroethane<br>DDT | C     | 260.0            | 1.9 x 10 <sup>-8</sup>          | 354.5            | 0.0031                               | 0.0028 (25°C)   | e, e, f, g, e |
| Aldrin  | C     | na               | 7.99 x 10 <sup>-7</sup>         | 364.93           | 0.2 (25°C)                           | 1.43 x 10 <sup>-3</sup> (25°C)                            | f, g, g       |
| Chlordane                                       | C     | 175.0            | 1 x 10 <sup>-6</sup>            | 409.80           | 0.056 (25°C)                         | 0.022 (25°C)  | f, d, f, d, d |
| Benzene   | D     | 80.1             | 10.13                           | 78.11            | 1800                                 | 0.478   | f, c, f, b, b |
| Toluene   | D     | 110.63           | 2.93                            | 92.14            | 577                                  | 0.562   | f, c, f, b, b |
| Methane   | D     | -164.0           | 27,260.0<br>(25°C)              | 16.04            | 24.1<br>(25°C)                       | 67.4<br>(25°C)  | f, g, f, g, g |

TABLE 8. USEFUL DATA FOR SELECTED ORGANIC CONTAMINANTS (CONCLUDED).

| Name                        | Group | Boiling point<br>°C | Vapor pressure<br>kPa <sup>a</sup> | Molecular weight | Aqueous solubility<br>mg/L <sup>a</sup> | Henry's Law constant<br>kPa m <sup>3</sup> /mol <sup>a</sup> | References    |
|-----------------------------|-------|---------------------|------------------------------------|------------------|---|--|---------------|
| n-Pentane                   | D     | 36.1                | 68.4<br>(25°C)                     | 72.15            | 38.5<br>(25°C)                          | 128<br>(25°C)  | f, g, f, g, g |
| n-Octane                    | D     | 125.7               | 1.88<br>(25°C)                     | 114.23           | 0.66<br>(25°C)                          | 325<br>(25°C)  | f, g, f, g, g |
| Decane                      | E     | 174.1               | 0.175<br>(25°C)                    | 142.29           | 0.052<br>(25°C)                         | 500<br>(25°C)  | f, g, f, g, g |
| 1,2,3-Trimethyl-<br>benzene | E     | 176.2               | 0.202<br>(25°C)                    | 120.2            | 75.2<br>(25°C)                          | 0.323<br>(25°C)  | f, g, f, g, g |
| Benzopyrene                 | F     | 177.8               | 6.67 x 10 <sup>-13</sup><br>(25°C) | 252.31           | 0.0012<br>(25°C)                        | 1.40 x 10 <sup>-9</sup><br>(25°C)                            | f, g, f, g    |
| Acetone                     | G     | 56.2                | 24.8                               | 58.08            | infinite                                | 0.00402<br>(25°C)  | f, e, f, e, e |

<sup>a</sup>All values are for 20°C unless another value is noted.

b = Reference 38

c = Reference 39

d = Reference 40

e = Reference 41

f = Reference 37

g = Reference 42

na = not available



solvents) and retain them near the surface of the water table. In that case, partitioning between gaseous and organic phases becomes more important than the partitioning between gaseous and aqueous phases. Volatilization of VOCs from organic solvents is determined by the volatility of the solvent and the mole fraction of the solute in the solvent. For solvents other than complex hydrocarbon products, the volatility of VOCs from an organic phase can be estimated by Raoult's Law. Raoult's Law states that molar weights of nonvolatile non-electrolytes when dissolved in a definite weight of a given solvent, under the same conditions, lower the solvent's freezing point, elevate its boiling point, and reduce its vapor pressure equally for all such solutes (Reference 42). VOCs can be introduced directly to the soil gas phase without contaminating either soil grains or ground water. Underground utility lines often introduce volatile compounds to soil gas from cracks and/or joints in natural gas and sewer lines, for example, C<sub>1</sub> through C<sub>4</sub> aliphatic hydrocarbons (Group D) can be released from natural gas lines, and a variety of solvent and fuel vapors can diffuse from sewers carrying industrial wastes.

### 3. Hydrologic and Geologic Issues

Certain hydrologic and geologic features of the site may also be important to the success of a soil gas study. Subsurface diffusion barriers often result in soil gas VOC concentrations which are uncharacteristic of the underlying ground water. Of primary concern are clay lenses, perched water, buried foundations, and other potential barriers to the vertical diffusion of gaseous contaminants. Chemical concentration gradients are locally disrupted by diffusion barriers because gaseous contaminants are either absent or present at very low concentrations in soil gas overlying the barrier. A review of detailed lithologic logs prepared by a hydrologist or geologist during the installation of monitoring wells or borings in the investigation area can indicate whether these features are present.

The presence of diffusion barriers does not preclude a soil gas investigation as long as the areal extents of barriers are minimal compared to that of the subsurface plume. However, soil gas sampling is ineffective in a situation where a clean aquifer overlies a contaminated aquifer because contaminants are unable to diffuse through the unconfined aquifer. Mapping of subsurface plumes via soil gas sampling is usually not affected by a few anomalous points due to the large number of samples which are collected over an investigation site. However, the location of potential diffusion barriers should be identified before the interpretive phase of a soil gas study.

In addition to gas diffusion barriers, the presence of soil moisture and highly permeable zones (e.g. backfill or utility trenches) locally affect soil gas samples. High moisture levels reduce the air porosity of soils and inhibit both soil gas collection and gaseous diffusion. As the number of continuous air-filled pores is reduced (due to increasing water saturation), the mass of VOCs in soil gas also decrease. Representative soil gas samples are rarely obtained from soils with an air porosity below five percent. Conversely, backfill and gravels have high air porosities which often result in anomalously high VOC concentrations relative to the underlying ground water. These coarse materials are more permeable than the undisturbed soil and can provide a conduit for laterally diffusing gaseous contaminants.

#### 4. Interference from Surface or Subsurface Sources

If surface or shallow vadose zone contaminant sources overlie a major subsurface plume, anomalous data may result. Surface or shallow soil contaminant sources can adversely affect the interpretation of regional soil gas data. Soil gas probes can intercept laterally diffusing VOCs from a surface source as well as vertically diffusing VOCs from ground water. Thus, contaminant concentrations in shallow soil gas can be anomalously high, relative to concentrations in the underlying water. A radial distance equal to three times the depth to water has been empirically determined at several sites to be the extent of lateral contaminant diffusion surrounding a source. Soil gas samples collected beyond this distance are normally representative of the underlying ground water.

If surface sources are not identified prior to a soil gas investigation, they can be located using several techniques. Contaminant sources within the boundaries of a regional plume are indicated by: (1) an abrupt increase in soil gas contamination compared to surrounding points, (2) a change in chemical composition of the soil gas, and (3) a significant deviation from the soil gas/ground water concentration ratio calculated for an overall site. The presence of soil contamination can be confirmed by analyzing a vertical profile of soil gas. Vertical soil gas profiles completed near a surface spill typically show increasing VOC concentrations down to the depth of maximum soil contamination and then decreasing concentrations toward the water table. Contaminated ground water results in increasing VOC concentrations with depth from the ground surface to the water table.

#### C. COMPOUND-SPECIFIC INFORMATION

Once the Henry's Law constant and other physical properties are determined for the contaminant, site specific factors become important. These are discussed in detail below for each group. Key factors are the presence of the contamination in soil versus in ground water, the depth to the contaminated soil or ground water, and the physical state of the contaminants.

##### 1. Halogenated Methanes, Ethanes, and Ethenes (Group A)

The compounds in Group A possess low aqueous solubilities, high vapor pressures, high diffusion coefficients, and are relatively resistant to degradation processes in most soils. This makes them well suited for detection by soil gas sampling.

##### 2. Halogenated Propanes, Propenes, and Benzenes (Group B) and C<sub>9</sub>-C<sub>12</sub> Petroleum Hydrocarbons (Group E)

The depth to contaminated soil or ground water is important because compounds in Groups B and E have very low aqueous solubilities and readily partition out of the ground water. Once in the soil gas, however, these compounds remain near the water table or the original zone of soil contamination. Low vapor pressures and gas diffusion coefficients make Group B and E compounds amenable to soil gas analysis only where probes can be placed near contaminated soil or ground water. Since soil gas probes are normally driven to a depth of 1 to 3 meters below ground surface, there are obvious limitations to the remote detection of Group B and E compounds using conventional soil gas techniques.

### 3. Halogenated Polycyclic Aromatics (Group C) and Polycyclic Aromatic Hydrocarbons (Group F)

Groups C and F represent high molecular weight compounds which do not partition adequately into the gas phase to be detected in soil gas under normal circumstances. These compounds are of considerable environmental concern. However, they are not amenable to soil gas detection as described here. All other contaminant groups contain compounds with a significant vapor phase.

### 4. C<sub>1</sub>-C<sub>3</sub> Petroleum Hydrocarbons (Group D)

The low molecular weight hydrocarbons (Group D) have a density less than that of water and will float as a thin film on the water table. The aromatic components of Group D (e.g. benzene, toluene) are moderately water-soluble and therefore, occur as dissolved as well as immiscible contaminants. Group D compounds are affected by the depth to subsurface contamination sources because they are oxidized in the shallow soil. These compounds have high Henry's Law constants (indicating favorable partitioning out of the aqueous phase) and diffuse rapidly when introduced to the gas phase. Thus, Group D compounds should migrate into the shallow soil gas in any environment which permits subsurface diffusion of volatile organic chemicals. The residence time of Group D compounds in shallow soil depends on subsurface redox potentials and microbial activity. Low molecular weight petroleum hydrocarbons are most predictably detected in shallow aquifers or from leaking underground tanks where probes can be driven near the source of contamination.

### 5. Low Molecular Weight Oxygenated Compounds (Group G)

Many compounds in Group G have densities less than 1.0 gram/ml., but are seldom encountered as floating product due to their high aqueous solubility. The distinction of whether the contamination is present in the soil or the ground water is of particular importance for compounds in Group G which have high vapor pressures but which are also very water-soluble. The result is that these compounds diffuse quite readily once in soil gas but remain dissolved in the ground water. Hence, Group G contaminants are amenable to soil gas detection if they result from a surface or vadose zone spill, but may not be present in soil gas as a result of moderate ground water contamination.

To summarize, C<sub>1</sub> and C<sub>2</sub> halogenated hydrocarbons (Group A) are good candidates for soil gas detection under a wide range of environmental conditions. Compounds in this group partition readily out of ground water, diffuse rapidly, and resist biodegradation, making them prime candidates for detection using soil gas methods. The halogenated propanes, propenes, benzenes and the C<sub>8</sub>-C<sub>15</sub> hydrocarbons (Groups B and E) are most often detected as a result of shallow soil or ground water contamination because they diffuse minimally and tend to partition into aqueous or organic phases in the soil. Polycyclic aromatic hydrocarbons, PCBs, and organochlorine pesticides (represented by Groups C and F) are rarely, if ever, detected by soil gas sampling. Low molecular weight petroleum hydrocarbons (Group D) can either be detected in soil gas overlying shallow aquifers (where probes can be driven near the contamination source) or deep aquifers (where probes can be driven below the oxidative zone in soils). Volatile oxygenated compounds (Group G) are relatively water-soluble, and, therefore most easily detected as soil, rather than as ground water, contaminants in close proximity to the source. This information is summarized in Table 9.

TABLE 9. DETECTABILITY OF ORGANIC COMPOUNDS USING SOIL GAS METHODS.

| Group | Class  | Examples   | Vapor pressure | Detectable in  | Comments                                      |
|-------|--|--|----------------|----------------|---|
| A     | Halogenated methanes, ethanes, ethenes                 | CHCl <sub>3</sub> , CCl <sub>4</sub><br>TCA, PCE               | High           | Soil and Water | Diffuse rapidly. Resist biodegradation.       |
| B     | Halogenated propanes, propenes, benzenes               | DBCP, chloro-benzene   | Moderate       | Soil only      | Resist biodegradation. Minimal diffusion      |
| C     | Halogenated polycyclic aromatics<br>chlordane          | PCBs, aldrin, DDT,   | Very low       |                | Not good for soil gas analysis.               |
| D     | C <sub>1</sub> -C <sub>8</sub> Petroleum hydrocarbons  | Benzene, toluene, methanes, pentane, isooctane, JP-4, gasoline | High           | Soil and Water | Easily oxidized, Diffuse rapidly.             |
| E     | C <sub>8</sub> -C <sub>15</sub> Petroleum hydrocarbons | Diesel, Jet A, decane, trimethylbenzene                        | Low            | Soil only      | Some biodegradation. Low diffusion.           |
| F     | Polycyclic aromatic hydrocarbons                       | Motor oil, coal tar, benzo-pyrene                              | Very low       |                | Not good for soil gas analysis good for radar |
| G     | Low molecule weight oxygenated                         | Acetone, tetrahydrofuran, MEK.                                 | High           | Soil only      | Diffuse rapidly. Low air/water partitioning.  |

Note: MEK = methyl ethyl ketone.

For the electrical properties of these materials, see References 31 and 36.

#### D. DEVELOPING AN INVESTIGATIVE PLAN

When planning an investigation, the main objectives of the study will determine the spacing and siting of soil gas probes. Delineation of plume edges is most efficiently achieved by establishing a transect parallel to the hydraulic gradient and sampling outward from the suspected source. Once an initial boundary point is identified, subsequent sampling locations are selected on the basis of real-time results. By contrast, locating downgradient contaminant sources is best achieved by sampling soil gas on a predetermined grid covering the investigation site. Locating primary source areas is accomplished by either grid or real-time sampling, depending on the initial information which is available.

The distance between sampling points is a function of the plume resolution required. Soil gas samples are commonly collected on 300- to 600-meter (1,000- to 2,000-feet) intervals over large geographic areas where the objective is to identify potentially contaminated regions. Such widely spaced probes cannot provide resolution of individual plume characteristics. Plume definition is accomplished by sampling probes on more closely spaced centers, depending on the specific site.

Soil gas samples generally should not be collected less than approximately 15 meters (50 feet) apart where high resolution mapping is required. Differences in VOC concentrations between closely spaced points are as likely to result from small-scale heterogeneities in the shallow soil as from significant changes in the parameter of interest (e.g. contaminant levels in the underlying ground water). Locations of soil gas samples are also determined by the access to sampling areas and the ability to successfully drive probes into the underlying soil. Generally, the minimum spacing of soil gas probes is proportional to the depth to ground water.

The general topography and surface conditions at the site are factors to be considered for the selection of sampling depths. Changes in land elevation which result in significant differences in the depth to water over an investigation site may cause variations in soil gas concentrations. The thickness of the vadose zone overlying contaminated ground water affects chemical concentration gradients and thus the comparison of VOC concentrations in soil gas. Topography is a more critical factor for shallow aquifers (less than 6 meters below the ground surface) than for deeper ground water. When sampling above contaminated ground water less than 6 meters deep, probes are often driven to a constant height above the water table rather than to a constant depth below the ground surface. Several soil gas profiles can be used to determine the optimum depth of sampling for the study area. It is particularly important to sample below the zone of aeration/degradation so valid samples are obtained. This will generally be at least 0.6 meters (2 feet) deep.

Surface conditions also influence the choice of soil gas sample locations for a site. Extremely wet surface conditions caused by ponded water should be avoided because of problems associated with low air porosities in soil. Recently disturbed soils (e.g., plowed or graded) often do not yield representative soil gas results because of the dilution and mixing of soil gas with atmospheric air. If probes can be driven several feet below the disturbed soil, VOC concentrations in soil gas are usually representative of subsurface contamination.

The presence of manmade pavements covering soil may also affect the results of soil gas sampling. Asphalt or concrete surfaces can act as a barrier to the gaseous diffusion of VOCs and alter the chemical concentration gradient in shallow soil. Two adjacent probes sampled under exposed soil and pavement, respectively, can yield quite different soil gas concentrations. Generally, VOC concentrations sampled at the same depth are higher under pavement than under bare soil. This difference can affect data interpretation if soil gas samples are collected under both surfaces at the same site. Pavement materials vary widely in their ability to restrict the diffusion of VOCs.

If it is possible to drive a probe to ground water, ground water samples may be collected and analyzed for comparison to the soil gas samples. This approach provides data to test how well the ground water and soil gas data are correlated, which provides a measure of overall confidence in the study.

## E. INTERPRETATION OF RESULTS

Soil gas results are provided as concentrations for a specific location and depth. These are generally displayed as isopleth maps which show the areal extent of soil gas contamination for a specific depth. Vertical profiles may also be displayed; they are useful in justifying the choice of sampling depth and evaluating the source of contamination as described earlier.

Soil gas studies are usually performed to determine the extent of soil or ground water contamination or both. When ground water contamination is suspected, it is useful to compare soil gas and ground water concentrations. It is for this reason that during a soil gas study, ground water samples are usually collected from any available wells, or by driving the soil gas probe to ground water. Soil gas/ground water correlations are usually determined by placing soil gas probes near existing monitoring wells, or by sampling soil gas from the probe before it is driven to ground water. Linear regression analysis can then be used to calculate a correlation coefficient for log-log plots of soil gas vs. ground water concentrations. Anomalous concentrations are often indicative of contaminant sources or small-scale geologic/hydrologic heterogeneities in the vadose zone.

The concentrations of VOCs in ground water combined with the depth to water can be used to estimate chemical concentration gradients in soil gas. Contaminant flux rates are of interest because they provide an estimate of the migration time between contaminated ground water and shallow soil gas. Both contaminant flux rates and soil gas/ground water correlations are a function of chemical concentration gradients. Gradients are routinely measured in the field by sampling soil gas in a vertical profile.

Quality control for sample collection and analysis is important to consider in evaluating data. Vacuum pressure necessary to extract a sample is a useful parameter in judging the validity of a sample. If an impermeable zone is encountered with the sampling probe, this will be reflected by unusually high vacuum values. Consideration of other traditional quality control techniques applicable to analytical chemistry are also appropriate, such as comparison of duplicate, blank, and known sample results.

To summarize, isopleth plots, correlation and regression coefficients, and quality control data are all useful in developing a complete understanding of the soil gas data.

#### F. WHEN NOT TO USE SOIL GAS METHODS

Although soil gas methods have proven very useful in locating contamination, there are occasions when it should not be used. These occasions may be divided into two types, those when the method is not likely to detect contamination, and those when the method is not likely to be economical. There are a variety of reasons the soil gas method might not detect contamination. Properties of the contaminant are important in determining whether it will be detected. As explained earlier in this section, vapor pressure and the Henry's Law constant should be considered to determine whether a contaminant will be present in the vapor phase in sufficient quantities to be sampled. Site conditions, such as water-saturated soil with low air porosity, thick clay, an uncontaminated aquifer overlying a contaminated aquifer, or recently plowed or graded soil, may mean the soil gas method will be unsuccessful in identifying subsurface contamination. Site conditions also may mean that the soil gas method will not be economical, for example, if soil is impenetrable; or if ground water is so shallow that samples may be obtained directly. In these cases, the soil gas sampling technique should not be used.

## SECTION VII

### PLANNING A GEOPHYSICAL INVESTIGATION

#### A. USES OF GEOPHYSICS

The purpose of this section is to provide general guidance in the choice of geophysical techniques to detect organic contamination. Most geophysical techniques are useful in site characterization activities and have been developed for that purpose. Some techniques have capabilities which are useful for the detection of inorganics, while other techniques have capabilities which are useful in detecting organic contaminants. Table 10 reviews the characteristics of seven geophysical techniques, highlighting features of each method. It is intended to provide a capsule summary of the primary technical characteristics of each method, including parameter measured, mode of measurement, depth of penetration, resolution, and raw data format. Further information about uses of geophysics for determining depth to ground water, depth to bedrock, location of trenches, metal objects, and inorganic plumes may be found in Reference 21. It is essential that an experienced geophysicist conduct the investigations and interpret the data, because of the complexities of the techniques.

Table 11 summarizes common applications of the techniques. The categories listed are general: site characterization refers to detecting layers, depths of soil and rock, and depths to the water table; conductive leachate plumes refers to detecting the vertical and horizontal extent of inorganic leachates; metal objects refers to detecting objects such as drums, trash, pipes, and cables; and organic contamination refers to detecting the vertical and horizontal extent of organics floating on the water table, or present in massive quantities in the soil. This table presents generalizations which are applicable in most cases. However, exceptions exist because of the wide range of site conditions and project objectives.

It is important to realize that techniques will be useful at some types of sites, but not at others. This is chiefly due to the geologic conditions present, but also may be due to instrument capabilities or interferences which affect the performance of the techniques. For example, GPR is not effective in clay soils. All electrical methods are affected by nearby metal objects. Direct current resistivity performs best sounding for depth information while EM is better for an area-wide search. Magnetism will not detect glass, copper, stainless steel, or aluminum, but is excellent for ferrous iron. Seismic methods are affected by wind and airport noise, truck and train traffic, and working drill rigs. Seismic methods do not perform well in unconsolidated soil. In addition, interpretation of the data from these techniques is an important part of the process. Topographic corrections may be needed to present the data at a standard distance from the water table. By using mathematical models and supplemental field measurements, it may be feasible to remove the effects of buildings or utilities from the data. However, in complicated geological situations, this may not be possible.

Note that only two techniques are recommended for routine use in detecting organic contamination. The successful application of these techniques, GPR and complex resistivity, is discussed in more detail below. The dc resistivity



TABLE 10. CHARACTERISTICS OF THE 7 GEOPHYSICAL METHODS (ADAPTED FROM REFERENCE 21).

| Method                            | Responds to Change in  | Mode of Measurement  | Depth of Penetration   | Resolution  | Raw Data Format   |
|-----------------------------------|--|--|--|---|---|
| 1. Ground Penetrating Radar (GPR) | Primarily electrical properties, density and fluid content, but also metallic objects.   | Continuous profile at 0.4 km/hr. for detailed survey; 0.8 km/hr. for reconnaissance survey. Ground contact not necessary.                          | One to 30 meters typical--highly site-specific. Limited by fluids and soils with high electrical conductivity and by clay.                       | Most detailed of all six geophysical methods.   | Picture-like graphic display. Analog or digital tape.   |
| 2. Electromagnetics (EM)          | Bulk electric conductivity of soil, rock and pore fluids. Pore fluids tend to dominate.  | Continuous profiles to 0.5 to 15 meters depth. Station measurements 15 to 60 meters depth. Some sounding capability. Ground contact not necessary. | Depth controlled by system. Coil spacing 0.5 to 60 meters typical.   | Excellent lateral resolution. Vertical resolution of 2 layers. Thin layers may not be detected. | Numerical values of conductivity from station measurements. Stripchart and/or magnetic recorded data yields continuous profiling. |
| 3. Direct Current Resistivity     | Bulk electrical resistivity of soil, rock and pore fluids. Pore fluids tend to dominate. | Station measurements for profiling or sounding. Must have ground contact.  | Depth controlled by electrode spacing. Limited by space available for array. Instrument power and sensitivity become important at greater depth. | Good vertical resolution of 3 to 4 layers. Thin layers may not be detected.                     | Numeric values of voltage current and dimensions of array. Can plot profile or sounding curves from raw data.                     |

TABLE 10. CHARACTERISTICS OF THE 7 GEOPHYSICAL METHODS (AFTER REFERENCE 21) (CONCLUDED).

| Method                 | Responds to Change in   | Mode of Measurement  | Depth of Penetration   | Resolution   | Raw Data Format   |
|------------------------|---|--|--|--|---|
| 4. Complex Resistivity | Chemical reactions in ground.   | Same as dc resistivity except measured for specific frequency.   | Same as above.   | Same as above.   | Numeric values of impedance and phase at specific frequencies.  |
| 5. Seismic Refraction  | Seismic velocity of soil or rock which is related to density and elastic proportions. | Station measurements. Must have ground contact.  | Depth limited by array length and energy source.*                                  | Good vertical resolution of 3 to 4 layers. Seismic velocity must increase with depth. Thin layers may not be detected. | Numeric values of time and distance. Can plot time/distance graph from raw data.  |
| 6. Metal Detector      | Electrical conductivity of ferrous and nonferrous metals.                             | Continuous. Ground contact not necessary.  | Single 55 gal. drum up to 3 meters.** Massive piles 55 gal. drums up to 6 meters.  | Very good ability to locate targets.   | Relative response from audio/visual indicators. May record data.  |
| 7. Magnetometer (VLF)  | Magnetic susceptibility of ferrous metals.  | Continuous total field or gradient measurements. Many instruments are limited to gal. drums up to 20 meters. Ground contact not necessary. | Single 55 gal. drum up to 6 meters.** Massive piles 55 gal. drums up to 20 meters. | Good ability to locate targets.  | Non-quantitative response from audio/visual indicators. Quantitative instruments provide meter or digital display. May record data. |

\*Depth is also related to equipment capability.

\*\*Depth is very dependent upon instrument used.

TABLE 11. GENERALIZED APPLICATIONS OF GEOPHYSICS TECHNIQUES.

| Technique                      | Application           |                     |               |                       |
|--------------------------------|-----------------------|---------------------|---------------|-----------------------|
|                                | Site Characterization | Conductive Leachate | Metal Objects | Organic Contamination |
| Ground-Penetrating Radar (GPR) | yes                   | yes                 | yes           | yes                   |
| Electromagnetics (EM)          | yes                   | yes                 | yes           | possibly              |
| Resistivity (dc)               | yes                   | yes                 | yes           | possibly              |
| Complex Resistivity            | no                    | no                  | no            | yes                   |
| Seismic Refraction             | yes                   | no                  | no            | no                    |
| Metal Detector                 | no                    | no                  | yes           | no                    |
| Magnetometer                   | no                    | no                  | yes           | no                    |

\*In some cases, the organic contamination will be associated with inorganic contamination. Examples include organics in metal drums and mixed organic-inorganic leachate plumes.

and EM techniques may sometimes be useful at a site for detecting hydrocarbons, but the conditions for which this is true are not well understood. Other techniques with greater likelihood of success such as soil gas sampling should be considered first.

## B. CONSIDERATIONS IN DECIDING WHETHER TO USE GEOPHYSICS

### 1. General

When selecting geophysical techniques for a site investigation, many questions should be addressed. The following list of questions can help to better define the important decisions to be made for a given site investigation. Many of the questions have answers which apply to more than one technique. Thus, the questions have been organized into a group of questions which is general in nature, and additional groups of questions which are specific to certain techniques. The questions listed have been selected from an EPA-U.S. Geological Survey computerized expert system now in development.

Some of the questions in this category are asked in a different manner in the discussion of preliminary information provided in Section V. Because of their importance and for logical continuity, they are also included here.

- Was the source of contamination a single event, a continuous leak which has been repaired, or a continuing leak?
- Did the contaminants originate from a surface spill, deep injection, a leaking trench, a leaking landfill, a leaking underground storage tank, a leaking underground pipeline, a land treatment facility, a surface impoundment, or are the contaminants different, like an intact, lost barrel of waste?
- Where are the contaminants now? They may be present on the surface, in the unsaturated zone, in the saturated zone, or in all these areas.
- Is this an areal search, a depth search, or both? This will determine whether profiles or soundings are performed.
- What types of contaminants are present? Are there inorganic contaminants present which may serve as indicators of the presence of organic contamination? If so, geophysical methods for locating conductive plumes may be useful.
- Are there natural organics present such as from a farm, forest, or swamp? If complex resistivity is used, these organics may produce a measurable effect and be a complicating factor in the interpretation.
- Are the soils at the site preferentially water wet or organic wet? A soil is not wet by a liquid if the liquid forms beads on the surface of the soil. If the soil is preferentially organic wet, then it may be possible to detect the organics with EM.
- Are the organics mostly in the water phase, adsorbed on soil solids, or in the gas phase? This question is important to determining the applicability of EM (and soil gas) techniques.
- Do the organics and inorganics react in any way? Are the organics being modified by degradation, catalysis, or adsorption? This is important for the application of complex resistivity (and soil gas).
- Are volatile organics present at the surface? If so, soil gas techniques should be considered.
- What is the environment at the site? Examples are rural, suburban, urban, industrial, landfill, military base, service station.
- How much of the site is covered by buildings? What type of access is possible? Is it difficult to walk around the site, or is it possible to drive over most of the site with a vehicle such as a van? Is any of the site inaccessible due to property ownership, security reasons, safety hazards, or difficulties such as swampy conditions?

## 2. Resistivity, EM, Ground-Penetrating Radar, and Magnetic Techniques

Further questions which apply specifically to resistivity, EM, ground penetrating radar and magnetic techniques follow.

- Are there any metallic objects on or near the site? Metallic objects such as fences, pipelines, and electrical or telephone wires above or below ground may interfere with EM, dc or complex resistivity, GPR, and magnetometry. These type surveys may not be possible depending on the amount of the site surface which is covered.
- Are metallic well casings installed at the site? Casings may also affect EM, dc or complex resistivity, GPR and magnetometry measurements.
- Are pipelines cathodically protected? If possible, the cathodic protection should be turned off during surveys. Cathodic protection does not affect GPR.
- How much of the area is covered by concrete or asphalt? Direct current and complex resistivity techniques require contact with the ground. Rebar present in the concrete may interfere with EM and magnetic measurements.
- What is the range in topographic relief across the site? If it is greater than 1 meter, then electromagnetic, resistivity, and ground-penetrating radar data should have a topographic correction applied.
- Are radio, television, or radar facilities nearby? Measurements may be affected.

### 3. Ground-Penetrating Radar and Complex Resistivity

Questions which are considered in the use of ground-penetrating radar and complex resistivity follow.

- Is clay present at the site? How much clay is present? Is it present as layers, lenses, even mixed with other soil components, or massive? GPR cannot penetrate clay. However, if the clay is present as lenses, the GPR may be useful between the lenses. The techniques of GPR and complex resistivity are complementary in that complex resistivity requires the presence of clay to be successful.
- Is the zone of relevance above the clay? If so, then GPR may be feasible.
- What are the properties of the contaminants? Are they soluble or insoluble in water? Are they miscible, immiscible, or a mixture of both? What is the density of the contaminants? Are they nonpolar, anionic, cationic or a mixture of these? GPR locates organics that phase-separate, i.e., are immiscible or insoluble, and float.
- What is the average electrical resistivity of the site in ohm meters? If the resistivity is greater than 30 ohm-meters, and clay is not present, then the site is a candidate for GPR.

Surface geophysical techniques have the ability to provide useful information at hazardous waste sites. Maps of electrical conductivity variation from EM measurements or resistivity soundings can provide three-dimensional boundary locations for hydrogeological and cultural features as well as direct

detection of inorganic contaminants. Direct detection of organics using these techniques may be possible in some cases. Complex resistivity and GPR require more time and expense, but can provide more detailed hydrogeological information and sometimes direct detection of organic contamination. GPR has the highest resolution of any geophysical technique, allowing it to "look" through the gaps in urban and high density utility environments. The data may require modelling to remove the effects of buildings. When most of the precipitation is seasonal, GPR data quality can be improved by performing the measurements during the driest time of the year or during the time when soils are frozen. GPR signals cannot penetrate some types of asphalt or closely spaced rebar or chicken wire. GPR is most useful at sites with no clay, on problems with water-insoluble organics above or floating on the water table. Complex resistivity is most useful at sites containing clay, and on problems with water-soluble organics below the water table. It also may provide an effective noninvasive monitor of the performance of clay barriers around waste sites.

#### 4. USGS Approach

Currently, the USGS has followed a very simple strategy at a number of sites for the possible detection of organic contamination (Reference 4). This strategy basically involves the initial determination of the electrical resistivity properties at a site. If necessary, this is accomplished through an initial EM survey. Direct current resistivity surveys could be used if cultural noise such as from a base radar system interfered with the EM survey. If a site is free of clay and has fairly high resistivity properties, greater than about 30 ohm meters, then a GPR survey could be conducted. The information in Table 12 "Susceptibility to Noise" can help determine whether cultural "noise" at a particular site could interfere with the above techniques and their chance for success.

If clays are present and the resistivity properties are less than 30 ohm meters, the chance of ground-penetrating radar surveys giving any penetration in the earth and producing any usable data is very small. In this situation, the USGS is currently investigating the use of the complex resistivity method. In some cases, this method has produced promising results for organic contamination detection (Reference 4). At this time, there are many unanswered questions, such as the physical properties of many of the organics and how they interact with the clay minerals. Further research for both laboratory and field studies is being conducted.

#### C. WHEN NOT TO USE GEOPHYSICAL METHODS

Although geophysical methods have proven very useful in characterizing sites and somewhat useful in locating contamination, there are occasions when these techniques should not be used. These occasions may be divided into two types, those when the methods are not likely to detect contamination, and those when the methods are not likely to be economical, compared to the alternatives. There are a variety of reasons the geophysical methods might not detect contamination. Specific characteristics of the individual methods described earlier may preclude their use in certain instances, for example, ground penetrating radar cannot be used successfully in clay environments. Specific site characteristics described earlier, such as the presence of metal fences and pipelines or steel reinforcement in concrete may prevent any useful measurements. Site

TABLE 12. SUSCEPTIBILITY OF GEOPHYSICAL METHODS TO "NOISE" (FROM REFERENCE 18).

| SOURCE<br>OF NOISE                  | RADAR  | EM                                | RESISTIVITY   | SEISMIC                                    | MD                        | MAG                                  |
|-------------------------------------|--|-----------------------------------|---|--|---------------------------|--------------------------------------|
| Buried Pipes                        | will detect,<br>but may<br>affect data             | 1<br>only if<br>close to<br>pipe  | 1<br>only if survey<br>is parallel and<br>close by          | 2<br>only if survey<br>is directly<br>over | 1<br>any metal<br>pipes   | 1<br>steel pipes<br>only             |
| Metal Fences                        | NA   | 1<br>only if<br>close to<br>fence | 2<br>only if survey<br>line is parallel<br>& close to fence | NA   | 2<br>only if<br>necessary | 1<br>steel fences<br>only            |
| Overhead Wires                      | 2<br>only if<br>unshielded<br>antennas<br>are used | 1                                 | NA  | NA   | NA                        | 2<br>some mags<br>respond            |
| Ground Vibrations                   | NA   | NA                                | NA  | 1  | NA                        | NA                                   |
| Airborne Electro-<br>magnetic Noise | NA   | 2                                 | 2   | NA   | 2                         | 1 to 2<br>(Earth's Field<br>Changed) |
| Ground Currents<br>and Voltage      | NA   | NA                                | 2   | NA   | NA                        | NA                                   |
| Trees                               | 2<br>only if<br>unshielded<br>antennas are<br>used | NA                                | NA  | 2<br>(Wind noise)                          | NA                        | NA                                   |

(Continued)

TABLE 12. SUSCEPTIBILITY OF GEOPHYSICAL METHODS TO "NOISE" (FROM REFERENCE 18) (CONCLUDED).

| SOURCE OF NOISE   | RADAR                              | EM               | RESISTIVITY      | SEISMIC | MD               | MAG                  |
|---|------------------------------------|------------------|------------------|---------|------------------|----------------------|
| Metal from Building, Vehicles, etc.   | 2 only if nearby antennas are used | 2 only if nearby | 2 only if nearby | NA      | 1 only if nearby | 1 only if nearby     |
| Small Metallic Debris on Surface or Near Surface (nails, wire coathangers)  | 2                                  | NA               | NA               | NA      | 1                | 1 ferrous metal only |
| Large Metallic Debris on Surface or Near Surface (Drums, Drum Covers, etc.) | 2                                  | 2                | 2                | NA      | 2                | 1 ferrous metal only |
| Susceptible to noise from ground contact/electrode problems                 | 2                                  | NA               | 1                | 2       | NA               | NA                   |

Note: This table shows the susceptibility of the geophysical methods to various forms of "noise" which may influence field operation, resulting data and subsequent interpretation.

MD - Metal Detector  
MAG - Magnetometry  
NA - Not Applicable  
1 - Very Susceptible  
2 - Minor Problem

\*Depth is also related to equipment capability.  
\*\*Depth is very dependent upon instrument used.



conditions also may mean that some geophysical methods will not be practical, for example, if terrain is inaccessible and a vehicle is required as in the case of some ground penetrating radar measurements. The geophysical techniques may not be economical when compared to soil gas measurements. In this case, if soil gas methods are likely to perform well, they should be used. In each case, the objectives of the investigation and the types of information which can be gained from each technique should be carefully considered.

## SECTION VIII

### CONCLUSIONS

Monitoring techniques tested under this project included active and passive soil gas sampling and analysis, and the geophysical techniques of electromagnetic induction, direct current resistivity, seismics, and magnetics. Field studies were performed at four Air Force bases; these techniques were used as appropriate. Active soil gas measurements were performed at all sites; resistivity and EM measurements were performed at three sites; and passive soil gas sampling was performed at two sites. The other techniques were performed at one site only.

The active soil gas sampling technique successfully mapped solvents, gasoline, and JP-4 contamination at all four bases where it was used. Results from one site demonstrated that the choice of sampling depth can influence the measurements obtained. Thus, it is important to perform depth profiles at the beginning of a study. The real-time nature of this method also represents a significant advantage since the choice and number of sampling locations can be evaluated as data are obtained. Because the active method is usually very reliable and has been used successfully at a large number of sites, its use is recommended until the passive soil gas method is better understood.

The passive soil gas technique was not as successful as the active technique in detecting contaminated ground water and may be prone to false negatives. However, because of its lower cost, this method has potential for reducing site investigation costs in some cases. Further testing of the performance of this technique for a variety of contaminants and geologic conditions is recommended before the method is used widely.

The geophysical methods were successful for site characterization, but the EM and dc resistivity techniques did not detect gasoline and JP-4 contamination when it was present. The natural variations in background resistivity masked any resistivity anomaly due to the presence of hydrocarbons. Based on these results from a limited group of geologic settings, the use of EM and direct current resistivity for direct detection of hydrocarbons appears to be a subtle technique which depends on a thorough understanding of background information at the site, the skill of the instrument operator, and may depend on the length of time the spill has been present. This does not preclude the more routine use of these techniques in hydrologic and geologic characterization. The techniques of ground-penetrating radar and complex resistivity were not demonstrated at the bases, but their successful performance in detecting hydrocarbons has been documented in the literature.

## SECTION IX

### RECOMMENDATIONS

A number of recommendations were developed during the course of this project. These are listed below, organized by technique.

#### A. SOIL GAS TECHNIQUES

Soil gas sampling is a relatively new monitoring technique. Both the active and passive sampling methods need further evaluation in a variety of geologic conditions so that standardized sampling and analytical approaches can be developed. Further investigation of the passive sampling technique might lead to methods which could minimize some of the existing problems. Developing these standardized approaches is a goal of the American Society for Testing and Materials (ASTM) specialty group for this topic. As the Air Force gains experience with this technique, participation in this group should be considered.

Additional work to determine Henry's Law constants and other physical parameters for organic compounds which are unique to the Air Force operations would be useful in the preliminary decision making stage when site investigations are planned. These unique compounds include some jet fuels and solvents.

Finally, more general research on issues such as optimum selection of sampling locations, influence of sampling manifold shape and pumping rate on measurements, and influence of rainfall, temperature, and barometric pressure on measurement comparability will be important to a full understanding of these techniques.

#### B. GEOPHYSICAL TECHNIQUES

Geophysical techniques have been widely used in oil and mineral exploration, but have only recently been applied to shallow investigations at spills and hazardous waste sites. Developing the physical basis for understanding the detection of organics with electrical methods is of prime importance. While some basic work has been performed, further laboratory research on electromagnetic response of organics in sand and clay is needed. This type of investigation can be performed in a sand box type arrangement, using a variety of soils and contaminants.

Complex resistivity is a promising technique which needs further investigation and demonstration. It might be feasible to perform some of these demonstrations at Air Force bases where other techniques have not been successful. Complex resistivity performs well in clay environments.

The co-occurrence of organic contamination with inorganic contamination means that in some cases, geophysical techniques can successfully predict the location of organics based on the location determined for inorganics. Further research is needed to determine the circumstances for which this approach will be successful.

Other topics for investigation include studying the effects of weather, particularly rain, frost, and snow, on measurement results.

Geophysical methods also are being standardized through an ASTM specialty group. The Air Force may want to participate in this process as it gains more experience with the techniques.

### C. INTEGRATED APPROACHES

Often when soil gas and geophysical investigations are performed, the initial results are used to define an area of excavation, and the excavation is performed. Opportunity is not available to evaluate the performance of the techniques used in the investigations. However, with advance planning at selected sites, it would be possible to coordinate the initial investigation results with the excavation process so that detailed soil sampling/analysis data could be obtained for comparison and confirmation of results. This detailed level of investigation would document concentrations as a function of depth and spatial extent, providing field data to be compared with the laboratory studies recommended above. This would lead to improvements of geophysical models and the measurement approaches used. While some of these type experiments can be performed in a laboratory sand box, it is also important to work with actual conditions in the field so that effects of spill aging, annual temperature cycles, and degradation are included.

Soon the EPA-USGS geophysics expert system will be ready for its initial distribution. The expert system addresses both geophysical and soil gas methods. Experience and case histories gained at Air Force bases could be useful in improving the expert system. Both EPA and the Air Force would benefit if interesting Air Force case histories could be shared for evaluation in terms of the expert system recommendations. It may be desirable to develop a customized version of the expert system for Air Force use.

## REFERENCES

1. Germeroth, R.M., and Schmerl, H., "Jet Fuel from the Ground Up," Civil Engineering, pp. 64-66, February 1987.
2. Valentine, R.M., and Kwader, T., "Terrain Conductivity as a Tool for Delineating Hydrocarbon Plumes in a Shallow Aquifer - A Case Study." IN: Proceedings of Surface and Borehole Geophysical Methods in Ground Water Investigations, pp. 52-63, February 12-14, 1985.
3. Saunders, W.R., Castle, R.W., and Foget, C.R., "Delineation of Subsurface Petroleum Spills Using Terrain Conductivity Measurements," IN: Proceedings of the 1983 Oil Spill Conf., Am. Pet. Inst./U. S. EPA/U. S. Coast Guard, San Antonio, Texas, 1983, pp. 415-417.
4. Olhoeft, G.R., "Direct Detection of Hydrocarbon and Organic Chemicals with Ground Penetrating Radar and Complex Resistivity," IN: Proceedings of the National Water Well Association Conference on Hydrocarbons and Organic Chemicals in Ground Water, Houston, November 12-14, 1986, pp. 284-305.
5. Baker, Allison T., LaBrecque, Douglas J., Marrin, Donn L., and Mazzella, Aldo T., Geophysical and Soil-Gas Investigations: Phelps Collins Air National Guard Base, Alpena, Michigan, TS-AMD-85580, prepared by Lockheed Engineering and Management Services Co., Inc. for U. S. EPA, EISL-LV, Las Vegas, Nevada, February 1987.
6. Pitchford, Ann M., Mazzella, Aldo T., and Scarbrough, Kenneth R., Geophysical and Soil-Gas Investigations at Holloman Air Force Base, New Mexico, ESL-87-47-I and ESL-87-47-II, Engineering and Sciences Laboratory, Air Force Engineering and Services Center, Tyndall AFB, Florida, November, 1987.
7. Mazzella, Aldo T., Pitchford, Ann M., and Scarbrough, Kenneth R., Geophysical and Soil-Gas Investigations at Robins Air Force Base, Georgia, ESL-IR-87-49, Engineering and Sciences Laboratory, Air Force Engineering and Services Center, Tyndall AFB, Florida, November, 1987.
8. Pitchford, Ann M. and Scarbrough, Ken R., Soil-Gas Investigations at Tinker Air Force Base, Oklahoma; ESL-87-48, Engineering and Sciences Laboratory, Air Force Engineering and Services Center, Tyndall AFB, Florida, November, 1987.
9. Kerfoot, H., and Mayer, C., "The Use of Industrial Hygiene Samplers for Soil-Gas Surveying," Ground Water Monitoring Review, Vol. 6, no. 4, pp. 74-78, 1986.
10. Kerfoot, H. B. and L. J. Barrows. Soil Gas Measurement for Detection of Subsurface Organic Contamination, Pre-Issuance Copy, U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, Nevada, 1987.

11. Lappala, E., and Thompson, G., "Detection of Ground-Water Contamination by Shallow Soil Gas Sampling in the Vadose Zone: Theory and Applications." IN: Proceedings of the 5th National Conference on Management of Uncontrolled Hazardous Waste Sites, Hazardous Materials Control Research Institute, Silver Springs, Maryland. 1984, pp. 20-28.
12. Marrin, D., "Delineation of Gasoline Hydrocarbons in Ground Water by Soil Gas Analysis," IN: Proceedings of the Hazardous Materials Management Conference West '85, Tower Conference Management Company, Wheaton, Illinois, pp. 112-119, 1985.
13. Eklund, B., Detection of Hydrocarbons in Groundwater by Analysis of Shallow Soil Gas/Vapor, API Publication 4394, May 1985.
14. Kerfoot, H.B., Kohout, J.A., and Amick, E.N., "Detection and Measurement of Ground-Water Contamination by Soil-Gas Analysis," IN: Proceedings of 3rd National Hazardous Wastes and Hazardous Materials Conference, Atlanta, Georgia, March 4-6, 1986.
15. Marrin, D.L., "Delineation of Gasoline Hydrocarbons in Ground Water by Soil-Gas Analysis," IN: Proceedings of the 1985 Hazardous Materials West Conference, Long Beach, California, December 3-5, 1985.
16. Marrin, D.L., "Remote Detection of Volatile Organic Contaminants in Ground Water via Shallow Soil-Gas Sampling," IN: Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Ground Water, Houston, Texas, November 5-7, 1984, pp. 172-187, National Water Well Association, Dublin, Ohio, 1985.
17. Devitt, Dale A., Evans, Roy B., Jury, William A., Starks, Thomas H., Eklund, Bart, and Gholson, Alex, Soil-Gas Sensing for Detection and Mapping of Volatile Organics. U. S. EPA, EML-IV, Las Vegas, Nevada, June 1987.
18. Voorhees, K.J., Application of a New Technique for the Detection and Analysis of Small Quantities of Contaminants in the Soil, Petrex Sales Literature, Denver, Colorado, (Unpublished manuscript, 1984).
19. Varian Gas Chromatographs. Sales Literature, 1988.
20. Sevik, J., Detectors in Gas Chromatography, Elsevier, New York, 1976.
21. Benson, R.C., Glaccum, R.A., and Noel, M.R., "Geophysical Techniques for Sensing Buried Wastes and Waste Migration," National Water Well Association, 1983.
22. Keller, G.V., and Frischknecht, F.C., Electrical Methods in Geophysical Prospecting, p. 517, Pergamon Press, New York, 1966.
23. McNeill, J.D., Electromagnetic Terrain Conductive Measurement at Low Induction Numbers, Technical Note TN-6, Geonics, Ltd., 1980.

24. Greenhouse, J., and Harris, R., "Migration of Contaminants in Ground Water at a Landfill: a Case Study, DC, VLF, and Inductive Resistivity Surveys," J. Hydrol., Vol. 3, pp. 177-197, 1983.
25. Zohdy, A., "Electrical Methods," in Techniques of Water Resource Investigations of the U.S. Geological Survey, Applications of Surface Geophysics to Ground-Water Investigations, Chapter D1, U.S. Government Printing Office, Washington, D.C., pp. 5-66, 1974.
26. Sumner, J., Principles of induced polarization for geophysical exploration, 277 pp., Elsevier, New York, 1976.
27. Olhoeft, G.R., "Clay-Organic Reactions Measured with Complex Resistivity," IN: Expanded Abstracts, 54th Annual International Meeting and Exposition of the Society of Exploration Geophysicists, Atlanta, Georgia, pp. 356-358, 1984.
28. Olhoeft, G.R., "Low-Frequency Electrical Properties," Geophysics, Vol. 50, pp. 2492-2503, 1985.
29. Olhoeft, G.R., "Applications and Limitations of Ground-Penetrating Radar," IN: Expanded Abstracts, 54th Annual International Meeting and Exposition of the Society of Exploration Geophysicists, Atlanta, Georgia, pp. 147-148, 1984.
30. Wright, D., Olhoeft, G., and Watts, R., Ground-Penetrating Radar Studies in Cape Cod: in Surface and Borehole Geophysical Methods in Ground Water Investigations, pp. 666-680, D.M. Neilson, ed., Worthington, Ohio, Nat. Water Well Assoc., 1984.
31. Kutrubes, D., "Dielectric Permittivity Measurements of Soils Saturated with Hazardous Fluids," MSc Thesis, Dept of Geophysics, Colo. School of Mines, Golden, Colorado, 1986.
32. Ulriksen, C.P., "Application of Impulse Radar to Civil Engineering," Ph.D. Thesis, Dept. of Civil Engineering, Lund Univ. of Tech, Finland, published in USA by Geophysical Survey Systems Inc., Nashua, New Hampshire, 1982.
33. Miller, R.D., Pullan, S.E., Waldner, J.S., and Haeni, F.P., "Field Comparison of Shallow Seismic Sources," Geophysics, Vol. 51, pp. 2067-2092, 1986.
34. Romig, P.R., ed., "Special issue--Engineering and Ground Water," Geophysics, Vol. 51, pp. 221-322, 1986.
35. Mabey, D.R., "Magnetic Methods", in Techniques of Water Resource Investigations of the U.S. Geological Survey, Chapter D1, Applications of Surface Geophysics to Ground-Water Investigations, U.S. Government Printing Office, Washington, D.C., pp. 107-115, 1974.
36. Akhadov, Y., Dielectric properties of binary solutions, Pergamon, New York, 1980.

37. Olhoeft, G.R., "Nonlinear Electrical Properties," in Nonlinear Behavior of molecules, atoms and ions in electric, magnetic, or electromagnetic fields, pp. 395-410, L. Neel, ed., Elsevier, New York, 1979.
38. Baizer, M.M., and Lund, H., eds., Organic electrochemistry, 2nd ed., Marcell Dekker, New York, 1983.
39. Saunders, W. R. and Cox, S. A., "Use of an Electromagnetic Induction Technique in Subsurface Hydrocarbon Investigations," IN: Proceedings of the First National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, National Water Well Association, pp 585-599, 1987.
40. Saunders, W. R., and Germeroth, R. M., "Electromagnetic Measurements for Subsurface Hydrocarbon Investigations," IN: Proceedings of the Petroleum Hydrocarbon and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration Conference, National Water Well Association, 1985.
41. Walther, E.G., Pitchford, A.M. and Olhoeft, G.R., "Strategy for Detecting Subsurface Organic Contaminants," IN: Proceedings of National Water Well Association/American Petroleum Institute Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, 1986.
42. Weast, R.C., ed., Handbook of Chemistry and Physics, The Chemical Rubber Company, Cleveland, Ohio, 1985-1986.
43. Howe, G. B., Mullins, W. E., and Rogers, T. N., Evaluation and Prediction of Henry's Law Constants and Aqueous Solubilities for Solvents and Hydrocarbon Fuel Components, ESL-TR-86-66, Engineering and Sciences Laboratory, Air Force Engineering and Services Center, Tyndall AFB, Florida, August, 1987.
44. Arthur D. Little, Inc., The Installation Restoration Program Toxicology Guide, Volume 1, Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, May, 1987.
45. Arthur D. Little, Inc., The Installation Restoration Program Toxicology Guide, Volume 2, Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, May, 1987.
46. Arthur D. Little, Inc., The Installation Restoration Program Toxicology Guide, Volume 3, Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, May, 1987.
47. Mackay, D., and Shiu, Wan Ying, "A Critical Review of Henry's Law Constants for Chemicals of Environmental Interest," J. Phys. Chem. Ref. Data, Vol. 10, No. 4, pp. 1175-1199, 1981.
48. Freeze, R. A., and Cherry, J. A., Groundwater, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1979.



49. Handman, E.H., Hydrologic and Geologic Aspects of Waste Management and Disposal: A Bibliography of Publications by U.S. Geological Survey Authors, Circular 907, Geol Surv., pp. 1950-81, 1983.
50. Payne, B. R., 1972, "Isotope Hydrology," Adv. Hydrosoci., 8, pp 95-138.
51. Cherry, J. A., Farzolden, R. N., and Frind, E. O., "Migration of Contamination in a Landfill: A Case Study 3 - Tritium as an Indicator or Dispersion and Recharge," Journal of Hydrol., Vol 63, pp 51-80, 1983.
52. Mackay, D.M., Roberts, P.V., and Cherry, J.A., "Transport of Organic Contaminants in Groundwater," Environ. Sci. Tech., Vol. 19, pp. 384-392, 1985.
53. Hult, M.F., ed., Ground-water contamination by crude oil at the Bemidji, Minnesota research site: U.S. Geological Survey Toxic Waste-Ground Water Contamination Study, 84-4188, U.S. Geol. Surv. Water Resources Investigations Report, 1984.
54. Nash, J., Traver, R. P., and Downey, D. C., Surfactant-Enhanced In Situ Soils Washing, ESL-TR-87-18, Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall AFB, Florida, September 1987.
55. Mattraw Jr., H.C., and Franks, B.J., eds., Movement and Fate of Creosote Waste in Ground Water, Pensacola, Florida: U.S. Geological Survey Toxic Waste--Ground Water Contamination Program, Open File Report 84-466, U.S. Geol. Surv., 1984.
56. Bradley, E., Trichloroethylene in the Ground Water Supply of Pease Air Force Base, Portsmouth, New Hampshire, OF-80-557, U.S. Geological Survey Water Resources Investigation, 1980.
57. Marrin, D., and Thompson, G., "Gaseous Behavior of TCE Overlying a Contaminated Aquifer," Ground-Water, Vol 25:1, pp. 21-27, Jan-Feb 1987.
58. Walther, E., LaBrecque, D., Weber, D., Evans, R., and van Ee, J., "Study of Subsurface Contamination with Geophysical Monitoring Methods at Henderson, Nevada," IN: Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Washington D.C., Oct 31-Nov 2, pp. 23-36, 1983.
59. Cherry, J. A., ed., "Migration of Contaminants in Ground Water at a Landfill: A Case Study," Journal of Hydrology, Vol. 63, pp. 1-197, 1983.
60. Seitz, H.R., Wallace, A.T., and Williams, R.E., "The Effect of a Landfill on a Hydrogeologic Environment," IN: Engineering Geology and Soils Engineering Symposium, 9th Proc., Idaho Dept. Hwys., Boise, p. 185-208, 1971.
61. LeBlanc, D.R., Sewage plume in a sand and gravel aquifer, Cape Cod, Massachusetts, U.S. Geological Survey Water Supply Paper 2218, 1984.

62. Nichols, W.D., Geohydrology of unsaturated zone at the burial site for low level radioactive waste near Beatty, Nye County, Nevada, U.S. Geological Survey Open File Report 85-198, 1986.
63. Beers, R., and Morey, R., Subsurface radar profiling field tests at low-level nuclear waste sites: Maxey Flats, Kentucky and Beatty, Nevada, NUREG-CR-1272, GC-TR-79-1023, U.S. Nuclear Regulatory Commission, 1981.
64. Ehrlich, G.G., Goerlitz, D.F., Gcdsy, E.M., and Hult, M.F., "Degradation of Phenolic Contaminants in Ground Water by Anaerobic Bacteria, St. Louis Park, Minnesota," Ground Water, Vol. 20, pp. 703-710, 1982.
65. Taylor, R.W., Evaluation of Geophysical Surface Methods for Measuring Hydrological Variables in Fractured Rock Units, OFR-17-84, NTIS PB84-158021, U.S. Bureau of Mines, 1984.
66. Davison, C.C., Keys, W.S., and Paillet, F.L., Use of Borehole-Geophysical Logs and Hydrogeologic Tests to Characterize Crystalline Rock for Nuclear Waste Storage, Whitshell Nuclear Laboratory, Ontario, Canada: Battelle ONKI, Columbus, Ohio, OHMI-418, 1982.
67. Olsson, O., Duran, O., Jantlid, A., and Stenborg, L., "Geophysical Investigations in Sweden for the Characterization of a Site for Radioactive Waste Disposal--An Overview," Geoexploration, Vol. 22, pp. 187-201, 1984.
68. Jones, J.W., Simpson, E.S., Neuman, S.P., and Keys, W.S., Field and theoretical investigation of fractured crystalline rock near Oracle, Arizona, NUREG/CR 3736, U.S. Nuclear Regulatory Commission Report, 1985.
69. Zehner, H.H., Hydrogeologic Investigation of Maxey Flats Radioactive Waste Burial Site, Fleming, Kentucky. U.S. Geological Survey Open File Report 83-133, 1983.
70. Franklin, A.G., Patrick, D.M., Butler, D.K., Strohm, W.E., Jr., and Hynes-Griffin, M.E., Foundation Considerations in Siting of Nuclear Facilities in Karst Terrains and Other Areas Susceptible to Collapse, NUREG/CR-206, U.S. Nuclear Regulatory Commission, 1981.
71. Dames and Moore, Installation Restoration Program Phase II - Confirmation/Quantification Stage 1 - First Draft Report for Holloman Air Force Base, New Mexico. Report for the United States Air Force Occupational and Environmental Health Laboratory, Brooks Air Force Base, Texas. 1985.
72. Coggin, J. H., "Induced Polarization Anomalies," Dissertation, University of California, Berkeley, California, Appendix IIA. 1971.
73. Water and Air Research, Inc. (WAR) Installation Restoration for Robins Air Force Base, Georgia, Phase II, Stage 2 - Field Evaluation. 1984.
74. Radian, 1984. Installation Restoration Program Phase II - Confirmation Quantification Stage 2, Draft Report for Tinker AFB, Oklahoma. Prepared for Brooks AFB, Texas, 78235, December 1985.

## APPENDIX A

### HOLLOMAN AFB

#### A. BACKGROUND

Holloman AFB is located in an arid alluvial valley in Otero County in central New Mexico, near the city of Alamogordo. At the BX Gasoline Service Station, a substantial amount of gasoline was lost from a leak in the underground pipes, creating a plume of floating product. The gasoline plume will be the focus of this discussion.

The BX Service Station and the location of the contamination based on ground water data are shown in Figure A-1. The BX Service Station is located in the main base area, near a school, hospital, convenience store, and base housing. The Service Station was built in the 1950s. In 1981, discrepancies were noticed in the fuel inventories. Excavation of the area around the tank showed that fuel had been leaking through corroded underground fuel lines. The loss was estimated at 450,000 to 680,000 liters (100,000 to 150,000 gallons).

#### B. GEOLOGY AND HYDROLOGY

Holloman AFB is located in a basin bounded on the east and west by tilted fault block mountains. In the vicinity of the base, the surface Cenozoic sedimentary deposits range in depth from 2,000 feet to 6,000 feet. The largely Tertiary fill is characterized by fine-grained sediments and caliche (calcium carbonate).

Average annual precipitation for the area is approximately 25 centimeters (10 inches). The basin is closed with respect to surface and ground water drainage; the surrounding mountains are the major source of ground water. The ground water beneath Holloman AFB is at a depth of approximately 1.5 to 5 meters (5 to 20 feet) and is highly mineralized. The uppermost aquifer is not used for drinking water, irrigation, or other purposes because of this poor water quality, the shallow depth from the surface, and the lack of a protective barrier.

#### C. METHODS USED

A variety of methods were applied during the Holloman AFB investigation. These methods included water-level and floating-product measurements, ground water sampling and analysis, soil gas sampling and analysis, and three types of geophysical measurements consisting of EM, resistivity soundings and pole-dipole profiling. These methods, and the rationale for choosing them are summarized in Table A-1. Figures A-2 and A-3 show the relative locations of the different measurements. Certain characteristics of the site influenced the application of these methods. For example, the water table is shallow, as mentioned above. This depth was important for choosing the soil gas sampling depth, and for determining the measurement intervals in the pole-dipole profiling.

Gasoline, which has significant VOC content, was known to be the contaminant. Thus, soil gas sampling was expected to be successful. Soil gas was collected from a total of 47 sampling points near the gas station, nine of

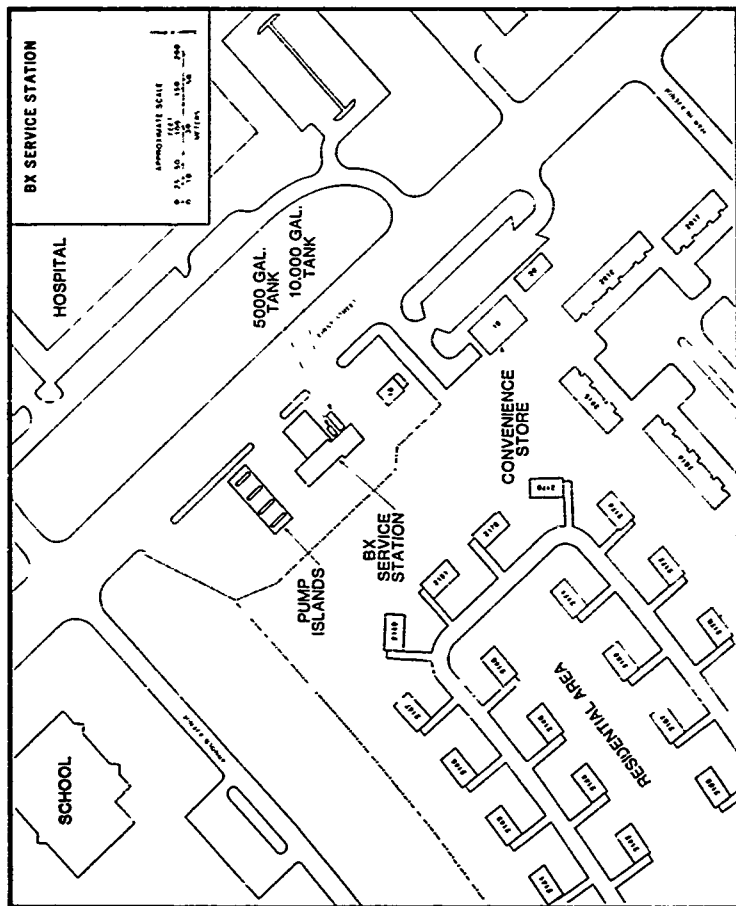
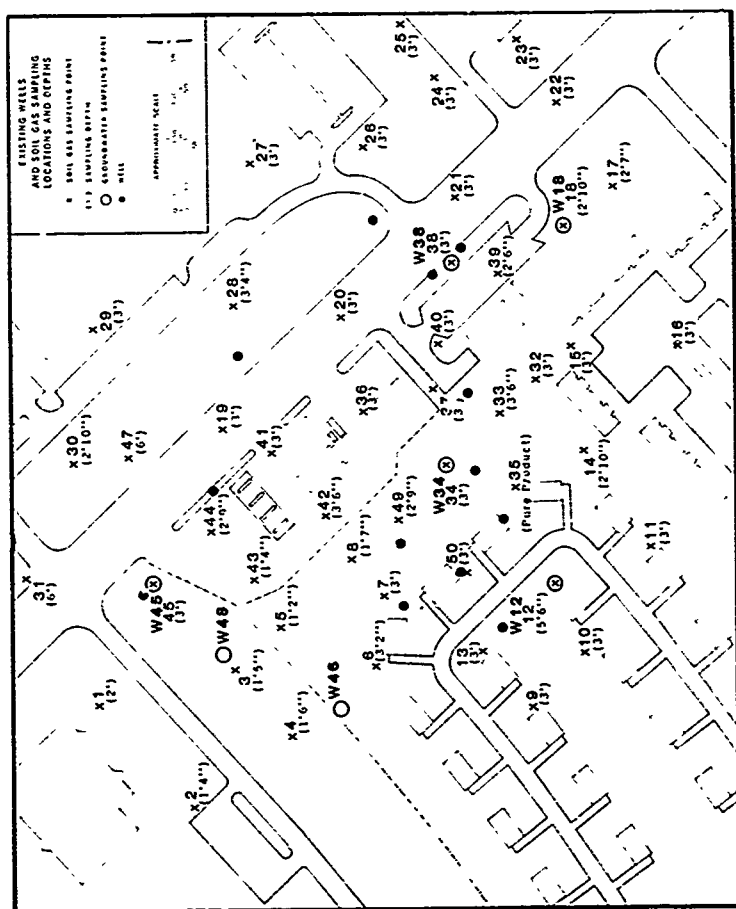
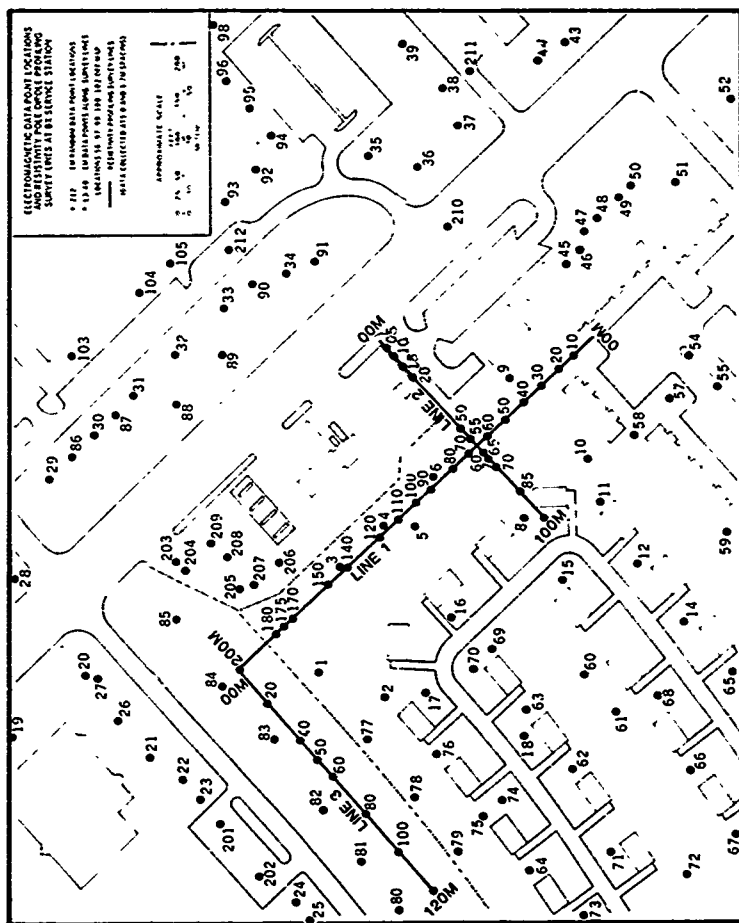


Figure A-1. BX Service Station, School, Hospital, Convenience Store and Residential Area at Holloman AFB.





**Figure A-3. Direct Current Resistivity and EM Measurement Locations at the BX Service Station, Holloman AFB.**

TABLE A-1. MEASUREMENT TECHNIQUES USED AT THE BX SERVICE STATION, HOLLAMAN AFB.

| Measurement; instrument  | Purpose   |
|--|---|
| Water Samples; pump, tubing; laboratory analysis using standard EPA methods          | Determine concentrations of organic and inorganic compounds in ground water and floating product. |
| Water level, depth of floating product; measuring tape, indicator paste              | Determine water level and the depth and thickness of floating layer of gasoline in wells.         |
| Soil gas; Tracor 540 Gas Chromatograph and Spectra Physics 4270 Computing Integrator | Determine concentrations of organic compounds in soil gas.  |
| Direct current resistivity, pole-dipole configuration; Bison Offset Sounding System  | Determine lateral and vertical changes in electrical resistivity.                                 |
| Electromagnetic Induction; Geonics EM-31   | Determine lateral changes in near-surface conductivity and locate buried metal pipes.             |

which were below paved surfaces and required the drilling of holes through concrete and asphalt. The target depth for sampling was 0.6 to 1 meter (2 to 3 feet) below ground surface. Ground water was sampled at 7 locations using the soil gas probe in addition to the 13 wells sampled using traditional methods.

The geophysical measurements were designed to detect a highly resistive layer floating on top of the water table. Pole-dipole resistivity profiles were performed with 1.7-meter and 5-meter dipoles along three transects, at locations chosen to avoid fences, the asphalt apron for the gas station, and streets and parking areas. The transects, labelled 1, 2, and 3, are 200, 100, and 120 meters long, respectively. An EM-31 survey was performed at 143 locations, selected for their distance from interfering fences and overhead power lines. Electromagnetic measurements were not made on a regular grid except when the measurements followed the resistivity transects. The locations chosen for these measurements were a compromise among accessibility, proximity to the contamination, and presence of overhead and underground utilities. The numerous buried pipes and overhead electrical wires made the use of a regular grid for the EM measurements impossible. It was also difficult to identify two unobstructed lines for dc resistivity measurements over the plume.

Electromagnetic and direct current resistivity profiling were performed by the EMSL-LV contractor, Lockheed Engineering and Management Services Company, Inc. (LEMSCO). Active soil gas sampling was performed by Tracer Research Corporation, Inc., under subcontract to LEMSCO. Ground water and floating

product samples were collected from 13 wells; these samples were analyzed by Western Technologies Laboratory, also under subcontract to LEMSCO.

#### D. GROUND WATER RESULTS

In the following discussions, hydrologic results are presented first, followed by ground water analyses, soil gas analyses, and geophysical results. This order was chosen so the measurements progress from most direct to most indirect. The ground water data form the fundamental data set to which the other types of data are compared. These surveys were performed at the base during June, July, and August, 1985. Since the ground water conditions are changing slowly at this site, data interpretation was performed with the expectation that conditions did not change significantly over the 3-month span.

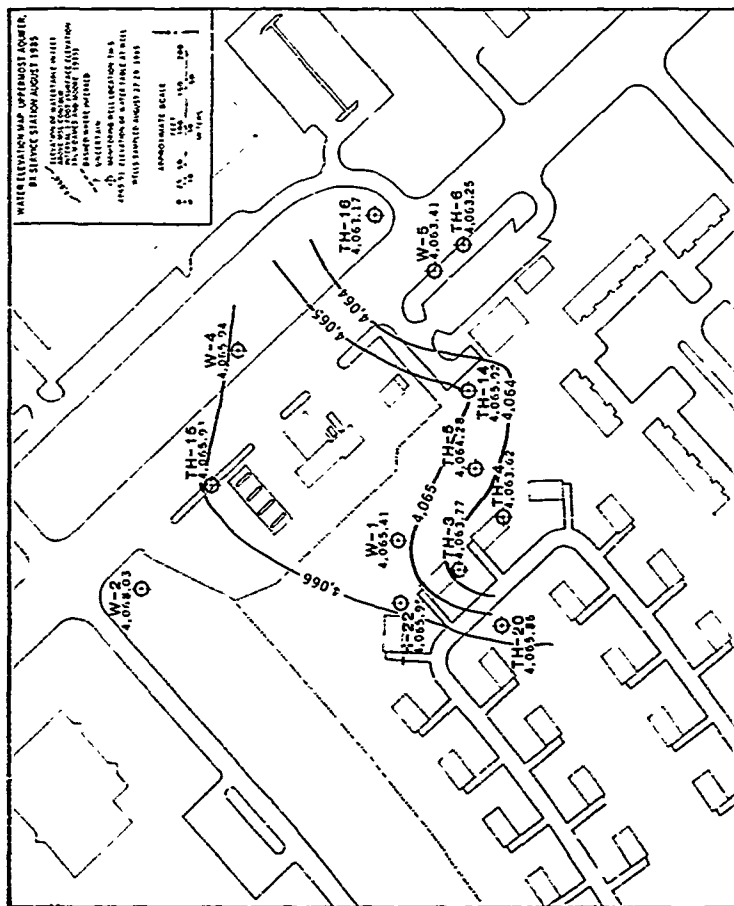
Figures A-4 and A-5 show contoured water table elevations and gasoline thickness, respectively. The water table elevations show gradients to the southeast and southwest depending on location. The two gradients are due to a mound feature in the general area of the gasoline station. Each of these wells is screened in a similar manner. Assuming the permeability of the soil around each well is similar, then the thickness of floating product will be proportional to the amount of product in the formation. However, the thickness in the well will be greater than the thickness of the product in the formation. These data show two areas of thick floating product; one along the street, in front of the convenience store, and the other at the west edge of the contamination near the residences. These areas are consistent with the ground water flow.

Ground water samples were analyzed for oil and grease, phenols, total organic halogens, total organic carbon, xylene, and toluene. All of these compounds are generally present but have low concentrations except for total organic carbon, xylene and toluene. These were found in high concentrations in samples of both ground water and floating product. Benzene analyses were not performed on the ground water samples, but were performed on the floating product samples. In the floating product samples, the ratio of concentrations of benzene to toluene to xylene was approximately 1 to 4 to 8.

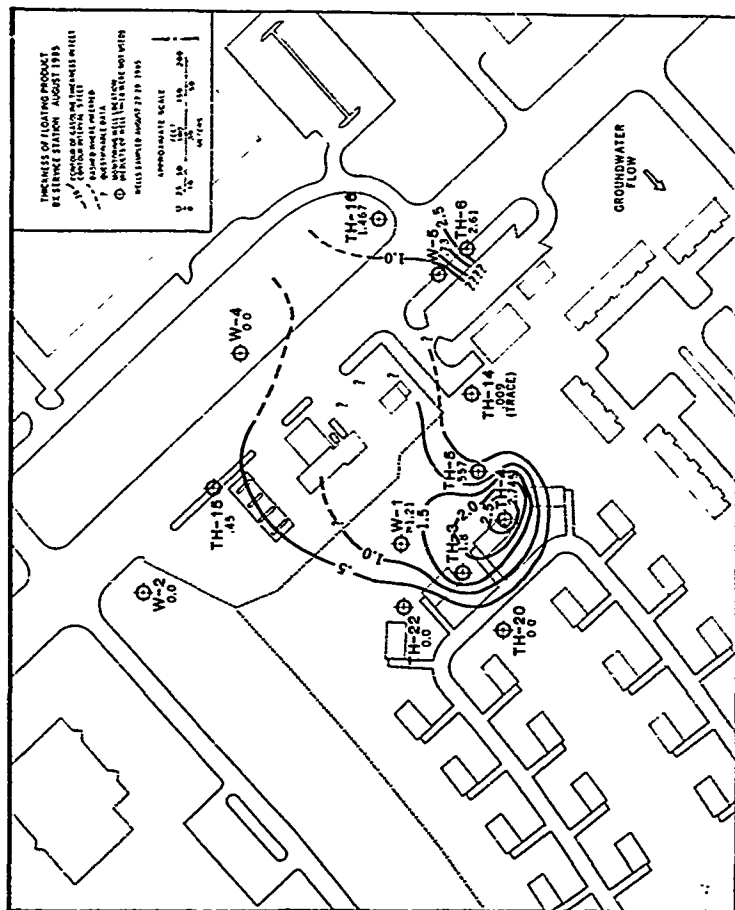
The contaminated wells are shown in Figure A-6. Two circles have been placed near each well in this figure. The upper circle represents floating product and the lower one represents ground water. The circles have been darkened to represent cases when concentrations of xylene and toluene are above background, and left blank to represent background concentrations. In two cases, at wells W-5 and TH-3, the floating-product thickness prevented the collection of ground water samples. In these cases, it was assumed that the ground water concentrations of xylene and toluene were above background. Well TH-14 near the center of the study area shows contaminated ground water; however, only a trace of floating product was identified at this well. The data for both floating product and ground water show the same general pattern; high concentrations in a roughly triangular pattern surrounding the BX Service Station.

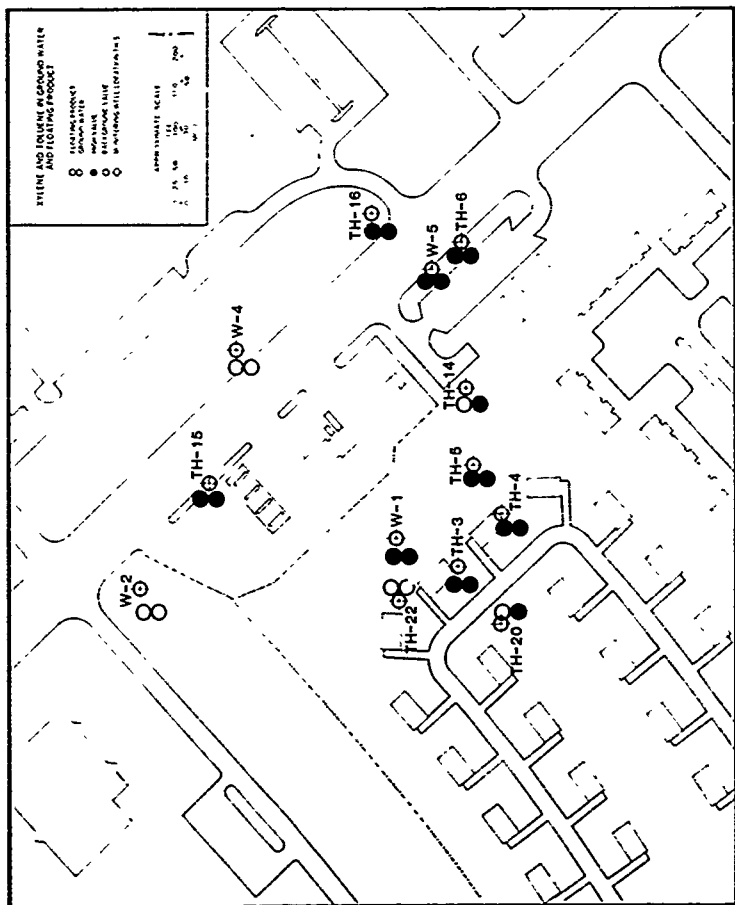
In summary, the results of the organic analyses of ground water and floating product show that the contamination is largely due to gasoline, not solvents or oil and grease. The analyses confirm that the floating product is a petroleum hydrocarbon. The contaminated wells are spread widely over the study area from





**Figure A-4. Water Table Elevation Map for the Uppermost Aquifer, BX Service Station, Holloman AFB.**





the north end of the Service Station near the pump islands, across the street to the east, and to the south and west near the residential area, forming a roughly triangular pattern.

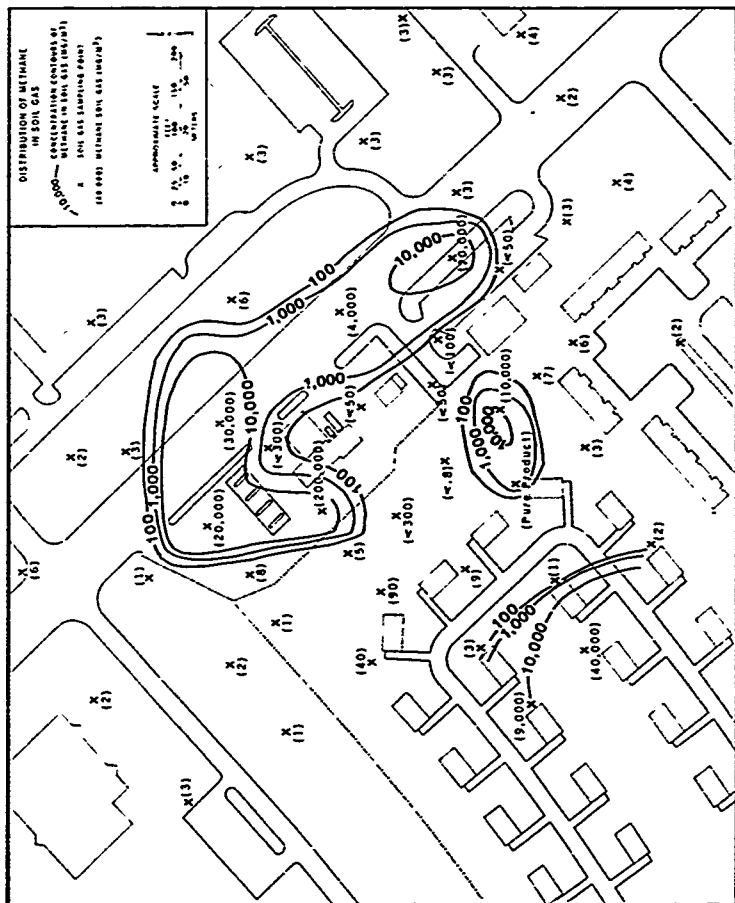
#### E. SOIL GAS RESULTS

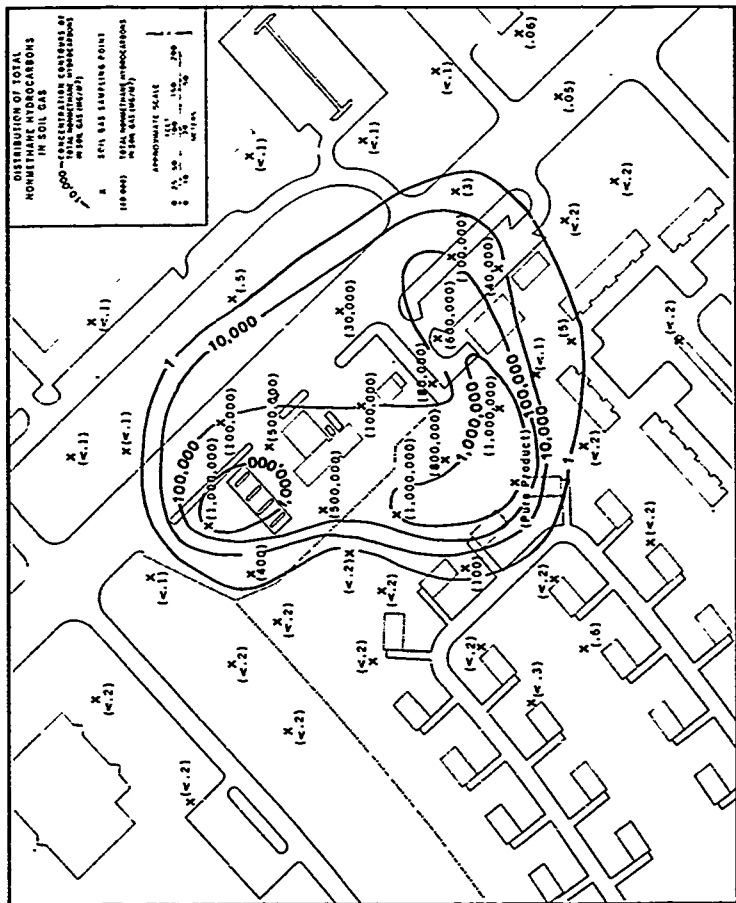
Soil gas samples were collected using an active method as described in Section II. These samples were analyzed for the presence of methane, benzene, toluene, o-xylene, 1,1,2-trichloro-trifluoro-ethane (F-113), 1,1,1-trichloro-ethane (TCA), trichloroethylene (TCE), perchloroethylene (PCE), ethyl benzene/xylenes, and total petroleum hydrocarbons. The ethylbenzenes/xylenes category included three aromatic hydrocarbons which were not separated by the chromatographic column. F-113, TCA, TCE, and PCE were not found in significant quantities. Contoured soil gas data for methane, nonmethane hydrocarbons, benzene, toluene, and o-xylene are presented in Figures A-7 to A-11. Each figure represents one organic compound or group of organic compounds.

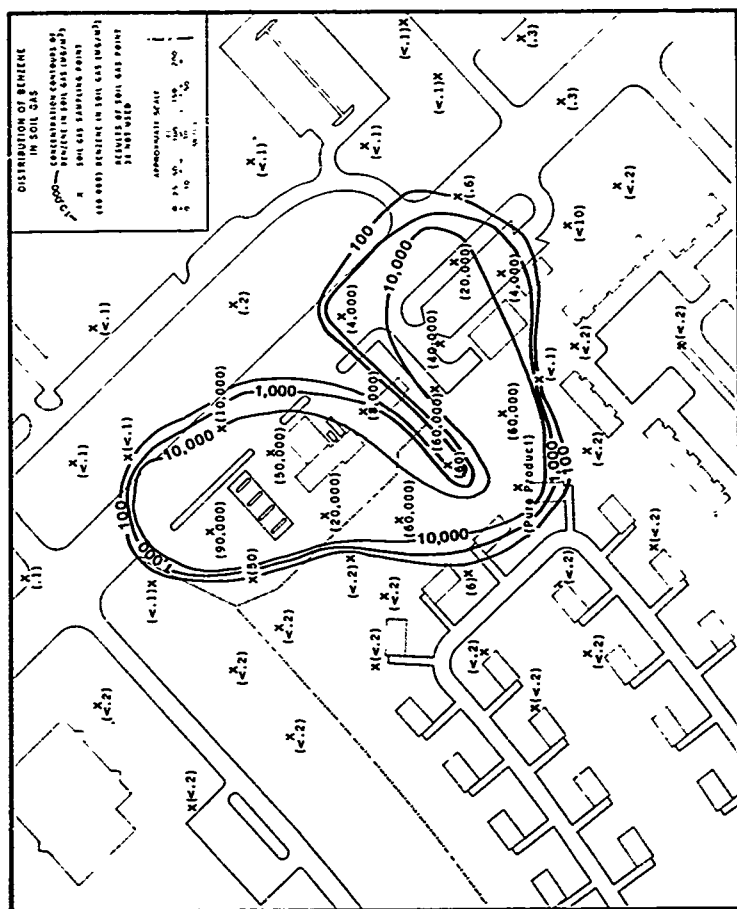
The soil gas data appear to delineate the contaminated zones indicated by the ground water samples rather well, even though the ground water and soil gas samples were not colocated. Except for methane, the patterns shown in these figures are very similar, forming a roughly triangular pattern around the BX Service Station. Since methane is a byproduct of biodegradation, the results for methane are not expected to match the other hydrocarbon concentrations closely. The boundary of the contamination appears to be fairly sharp, with steep gradients in the contamination over short distances. This is especially evident on the west side of the contaminant plume, near the residences. This shape can be explained in part by the ground water gradient described earlier.

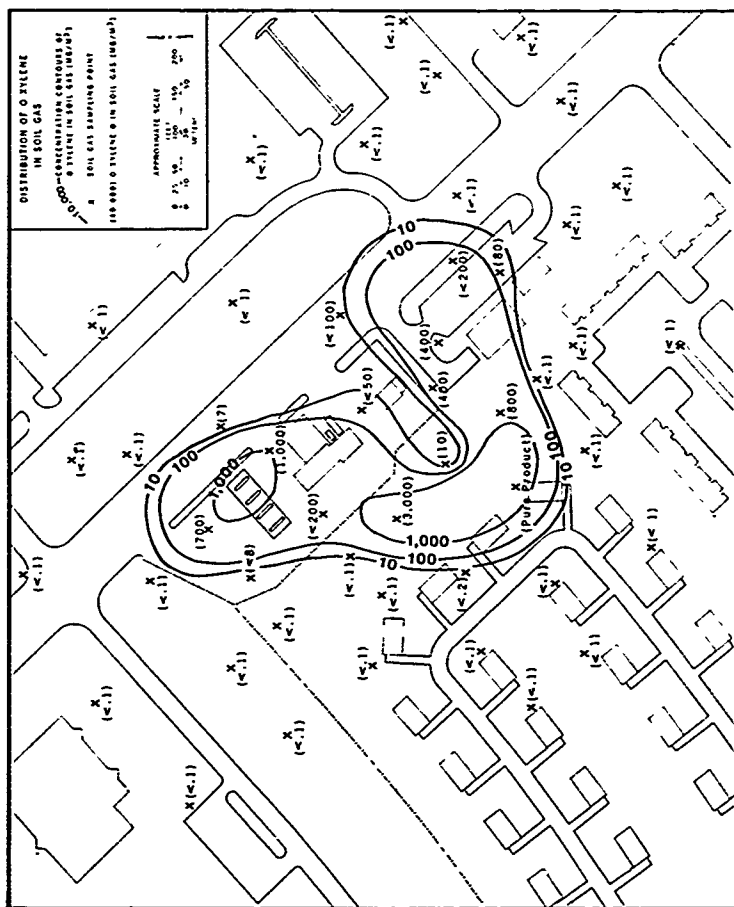
To compare the soil gas results with the ground water results, two approaches were used. In the first approach, data from colocated soil gas and ground water samples were compared. These samples were collected by inserting the soil gas probe, withdrawing a soil gas sample, and then allowing the hole to fill with water and collecting a ground water sample. Data for these five locations are shown in Table A-2. The absolute concentration values would not be expected to agree so the relative concentrations were compared. There was a good match in four of the five cases; however, for sampling point SG12/W12, ground water contamination was present but not indicated by the soil gas measurements. This location is on the westmost edge of the plume, near the residences.

In the second approach, data from soil gas, ground water, and floating-product samples from existing wells were compared using a circle plot, developed by adding soil gas data for toluene and xylene to the circle plot for ground water data. The resulting plot is shown in Figure A-12. In this case, since the soil gas samples were not a uniform distance from the wells from which the ground water samples were collected, the selection of sampling points for comparison could have been somewhat arbitrary. To minimize this, the nearest soil gas measurement was selected each time. However, this measurement was sometimes as much as 15 meters (50 feet) away. Even with this approach, Well TH-16 had no soil gas measurement closer than 30 meters (100 feet) so this well was dropped from the comparison. As before, circles were left blank for background values; the circles were darkened for higher values.











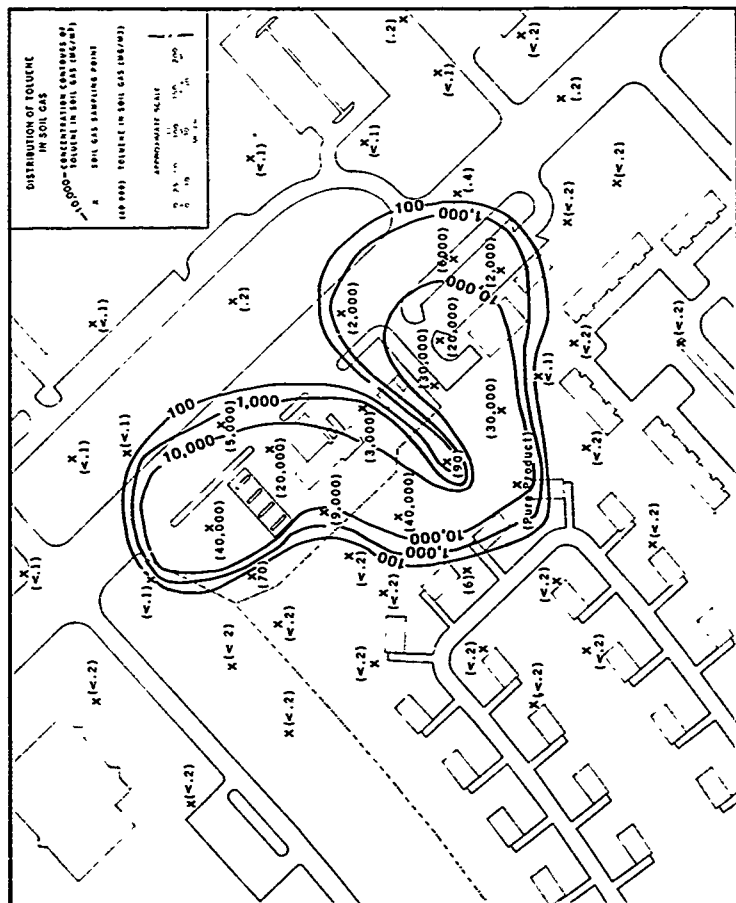
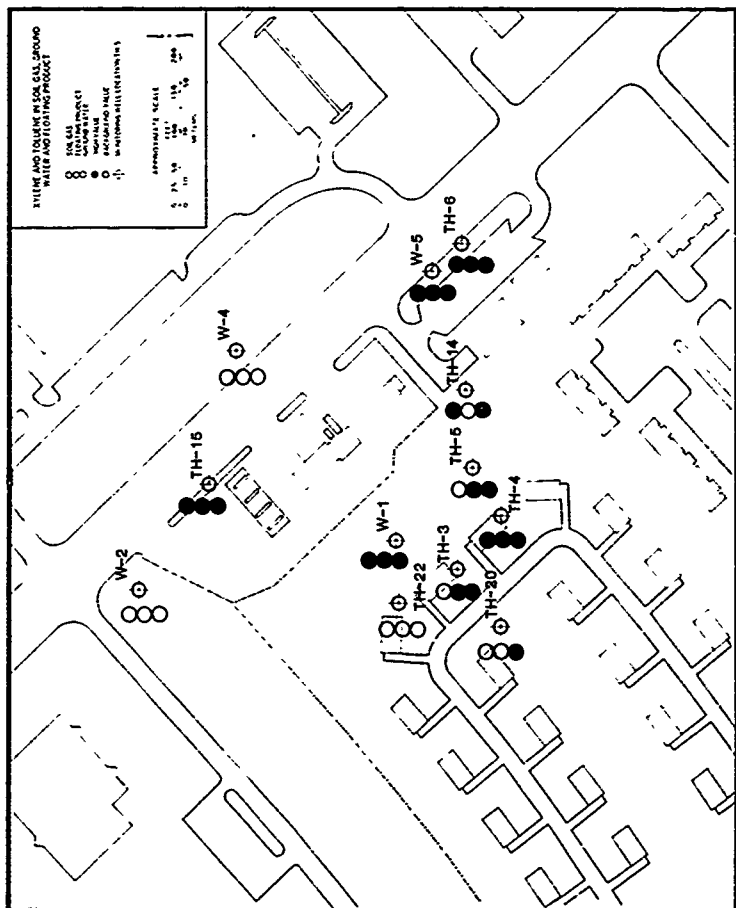


Figure A-11. Toluene Soil Gas Concentrations at the BX Service Station, Holloman AFB.



**Figure A-12.** Xylene and Toluene in Soil Gas, Ground Water, and Floating Product, BX Service Station, Holloman AFB.

TABLE A-2. SOIL GAS AND CORRESPONDING GROUND WATER CONCENTRATIONS OF TOTAL HYDROCARBONS AT THE BX SERVICE STATION, HOLLOMAN AFB

| Sampling location | Total hydrocarbons                          |                                   |
|-------------------|---|-----------------------------------|
|                   | Soil gas concentration (mg/m <sup>3</sup> ) | Ground water concentration (µg/L) |
| SG12/W12          | <0.2  | 200                               |
| SG18/W18          | <0.2  | <10                               |
| SG34/W34          | 700   | 100,000                           |
| SG38/W38          | 100,000                                     | 30,000                            |
| SG45/W45          | <0.1  | <5                                |

Note: The units mg/m<sup>3</sup> and µg/L are equivalent; the values can be compared directly. Both units are maintained in this table since mg/m<sup>3</sup> are traditionally used for soil gas measurements, while µg/L are traditionally used for water analyses.

The soil gas, ground water, and floating-product data agree at 8 of the 12 locations. At the four locations where these values do not agree, a number of different mechanisms may have been responsible. At locations where the measurements agree, the soil gas measurements could have been responding to a vapor gradient related to the presence of floating product. Well TH-20 represents the westmost extent of the contamination in the ground water. The lack of floating product at this location may explain the low concentrations measured in the soil gas. This well is near the location SG12/W12 discussed above. Well TH-3 is located at the outermost area of the contamination. In this case, the nearest soil gas measurement is apparently across the boundary of the contamination, and on the uncontaminated side. Wells TH-5 and TH-14 are between the center of the contaminated area and the west edge. This is puzzling because it was expected that the concentrations would be uniformly high in this area which is near where the leak occurred. Instead, some soil gas values are low, while others are high and the area appears to be inhomogeneous with contaminated ground water and floating product present at one well and only contaminated ground water present at another. The wells were installed at similar depths and with identical screens. Here it is possible that, again, the nearest measurement of soil gas is too far away for a valid comparison. Overall, given the difficulties of comparing data from points which are not strictly collocated, the soil gas values compare favorably with the ground water and floating-product data.

Additionally, in each case for ground water and soil gas, the highest concentrations occur at the points of the triangle, not near the center where the leak occurred. These locations are: (1) near the pump islands; (2) along and across the street, southeast of the station; and (3) near the residences, southwest of the residences. Very low values occur at locations where high values would be

expected, based on the local hydraulic gradient; i.e., Points 34, 36, and 39. Possible reasons for these characteristics include one or more of the following:

- movement of fuel in naturally-occurring zones of high permeability,
- effects of local ground water recharge,
- presence of additional leaks,
- effects of pumping during the recovery program, or
- effects of utility corridors.

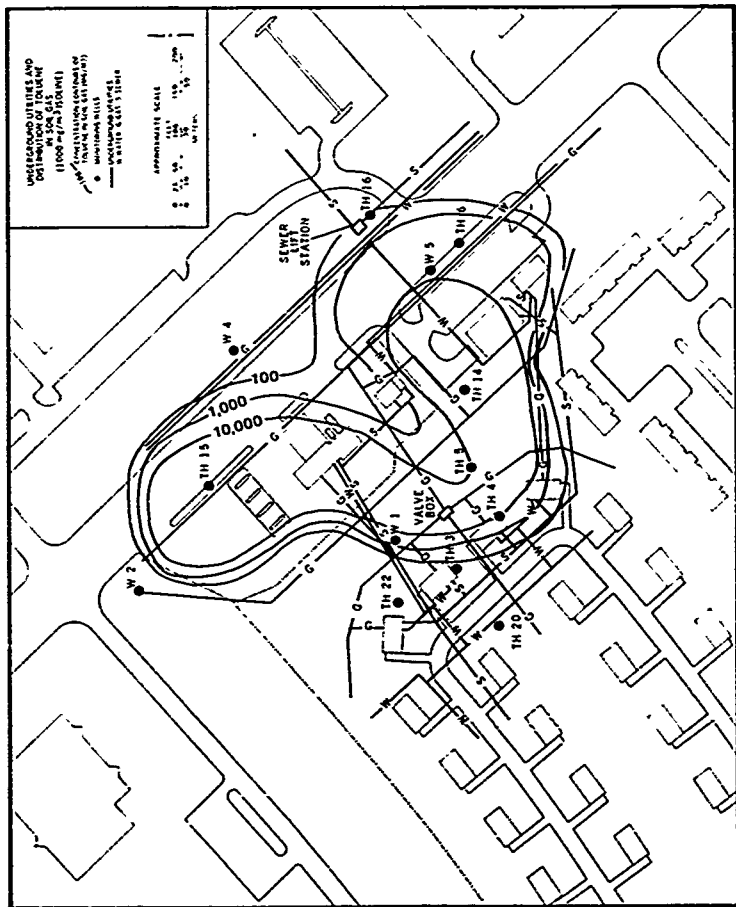
Figure A-13 shows the underground utilities in the vicinity of the gas station, along with the areas of highest concentration. Note the presence of water lines with the potential for connecting the leak to the areas of high concentrations both northwest and southeast of the station along the street, and across the street. The presence of water lines also offers a possible explanation for the high value to the southwest in combination with the low values measured at Point 34. The ground water gradients shown in Figure A-4 are consistent with the southeast and southwest directions of flow.

Movement of organic contamination along utility corridors has been observed before. If this is a possibility at a site, then the methods of choosing sampling locations should be reevaluated. In this case, sampling perpendicular to the known underground utilities should be considered to delineate the contaminated zones.

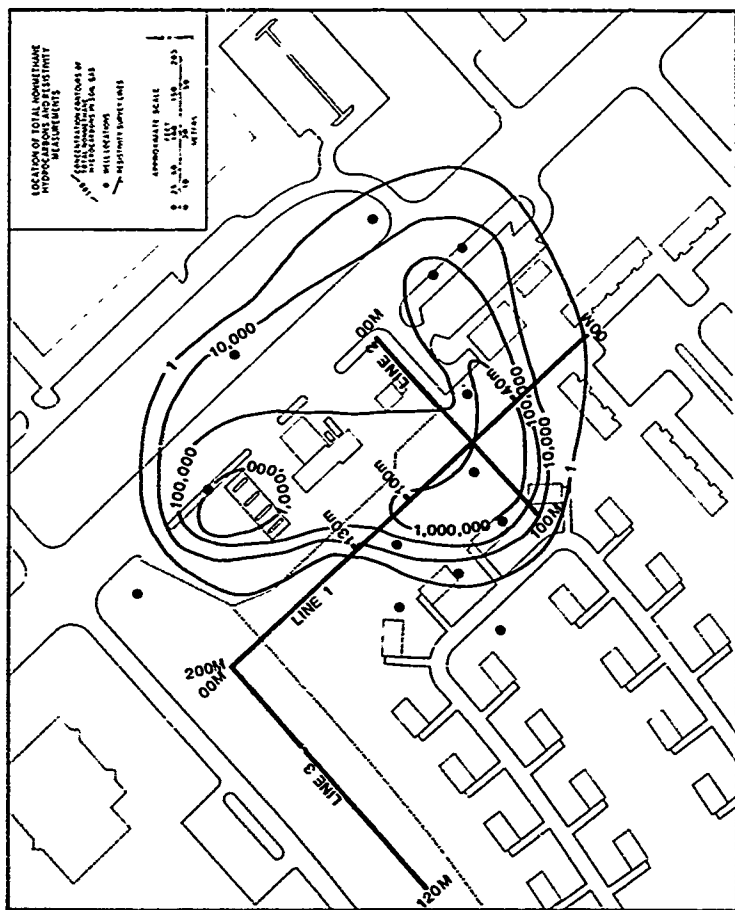
In summary, the soil gas data confirm the location and hydrocarbon content of the ground water contamination. The soil gas data depict a roughly triangular area of contamination around the Service Station similar to that depicted by the ground water data. When the relative concentrations of xylene and toluene in soil gas and ground water samples from the same location were compared, they show good agreement in four out of five cases. When further comparisons were performed using nearest soil gas neighbors to the existing wells, there was good agreement in 8 of 12 cases. For three of the four cases of poor agreement, this may have been due to the distance between the well and the sampling point. In the remaining case, low soil gas concentrations may have been due to the lack of floating product on the advancing edge of the plume. At this site, the edge of the soil gas plume may indicate the boundary for the floating product. Finally, a number of reasons were proposed for the high concentrations of VOCs in both soil gas and ground water at the apexes of the triangular contaminated area. The most intriguing of these possibilities is that the contamination is moving along underground utility corridors.

## F. GEOPHYSICAL RESULTS

Analysis of the geophysical data did not clearly reveal the location of the hydrocarbon contamination. Figure A-14 shows the dc resistivity lines in relation to the ground water contamination as indicated by the total nonmethane hydrocarbon concentrations in soil gas. The gasoline plume is located along Line 1 between stations 40 to 130, according to both the soil gas and ground water data. Further verification of the contamination is provided at a location about 5 meters from station 90 on Line 1, where a depth to the water table of 2 meters and a gasoline layer 0.4 meters thick were identified from a boring made when the wells were installed in 1984 (Reference 71). In contrast, Line 3 appears to be located in an uncontaminated background area; gasoline is apparently absent as indicated by the soil gas measurements.



**Figure A-13. Underground Utilities and the Distribution of Toluene in Soil Gas at the RX Service Station, Holloman AFB.**



**Figure A-14. Direct Current Resistivity Lines in Comparison to Total Hydrocarbon in Soil Gas at the BX Service Station, Holloman AFB.**

Figure A-15 provides two apparent resistivity pseudosections for typical contaminated and uncontaminated segments along Lines 1 and 3. This type of display is a plot of apparent resistivity data versus electrode spacings for different station locations, allowing a simple, quick visualization of the lateral and depth variations in the apparent resistivity. The pole-dipole data were converted to dipole-dipole data (Reference 72) and plotted as pseudosections as described above. Both pseudosections show variable resistivities laterally and as a function of depth. The apparent resistivity contours for the segment of Line 1 suggest a two-dimensional resistive body lies in the area of Station Locations 87 to 95. This may represent the gasoline layer. However, comparison of these results with those from an uncontaminated area is necessary to determine if this type of variability occurs naturally. Examination of the apparent resistivity variations in an uncontaminated segment from Line 3 shows variations which are very similar to those in the contaminated segment from Line 1. Thus, these variations probably reflect lateral changes in the geology. It appears that at this study area, the lateral changes in electrical resistivities due to naturally occurring two- or three-dimensional geological structure are on the same order of magnitude as those possibly due to the gasoline contamination. At this site, it is not possible to clearly delineate the presence of the gasoline data in the dc resistivity data. The use of additional geophysical methods may be able to separate out these effects.

The EM-31 vertical and horizontal dipole data are presented and contoured in Figures A-16 and A-17, respectively. These contours should be regarded with caution since spatial aliasing is probably present in the data. Spatial aliasing occurs when the distance between sampling locations is greater than the distance between significant changes in the data. It can be avoided by increasing the number of locations where measurements are made. In this case, this was not possible due to cultural effects that occurred throughout the area from pipelines and overhead powerlines. The apparent resistivity EM values are in general agreement with the dc resistivity measurements. However, the lateral resistivity variations indicated in the dc apparent resistivity data shown in Figure A-15 are not observed in the EM data. This is believed to be due to the large spacing between the EM-31 stations. Because of this spatial aliasing, it is not warranted to base any significant conclusions on the EM data.

#### G. SUMMARY

To summarize, at the BX Service Station at Holloman Air Force Base, the ground water data indicated a roughly triangular zone of contamination. The active soil gas data also depicted this generally triangular shape, with high concentrations at the apexes of the triangle. One of the more intriguing explanations is that the contamination moved through underground utility corridors. The geophysical results from EM and dc resistivity measurements did not separate the natural variations in resistivity from those that may have been caused by the presence of gasoline.

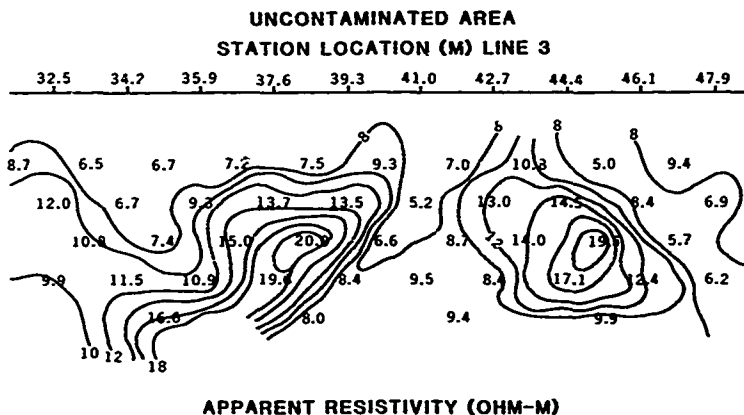
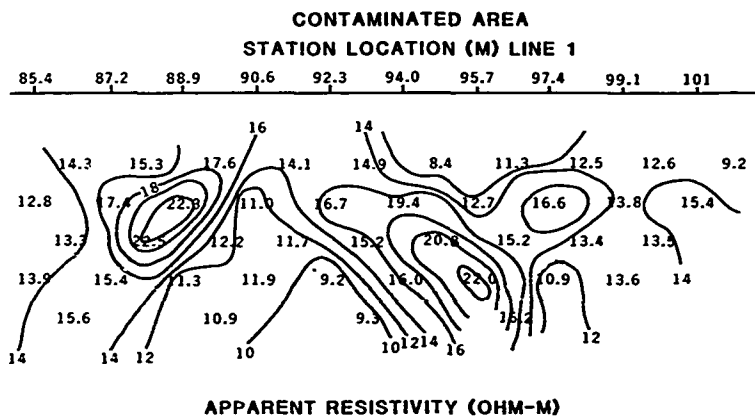
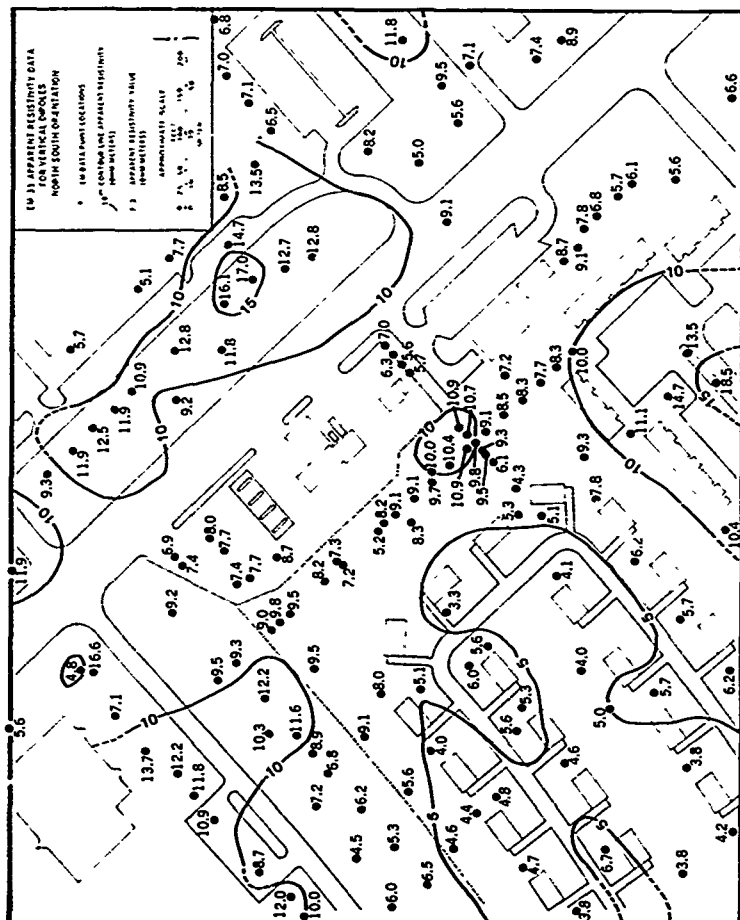
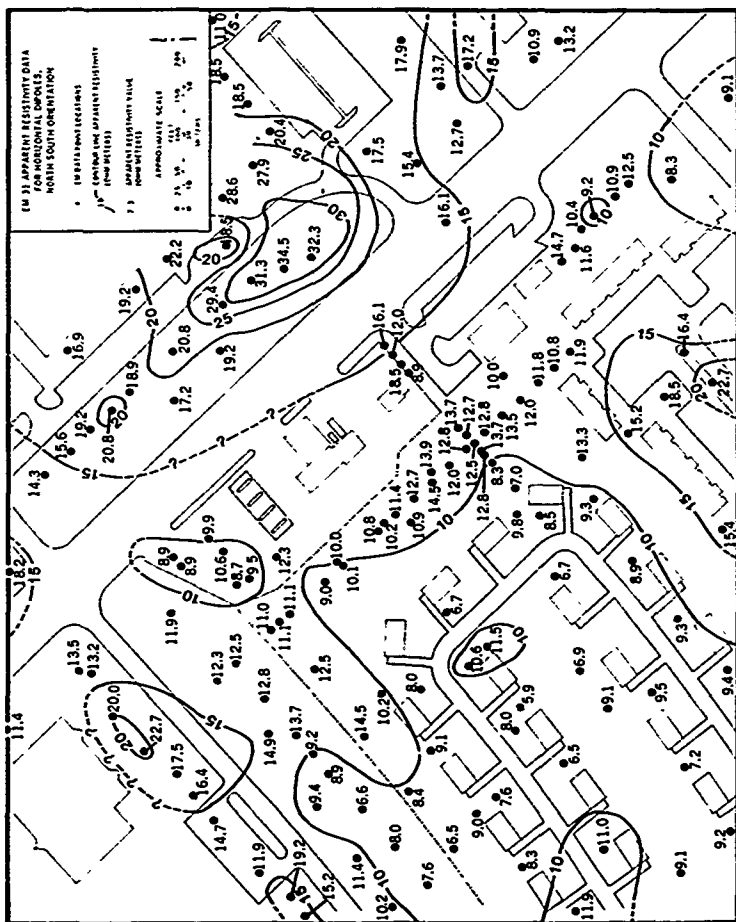


Figure A-15. Comparison of dc Resistivity Pseudosections for Contaminated and Uncontaminated Areas at the BX Service Station at Holloman AFB.







## APPENDIX B

### ROBINS AFB

#### A. BACKGROUND

Robins AFB is located approximately 20 miles south of Macon, Georgia, and is due east of Warner-Robins, Georgia. The results for the JP-4 Spill Site next to Landfill 1 will be highlighted in this discussion. Figure B-1 shows the relation of the study area to Landfill 1 and the new fuel farm.

During the mid-1960s an undetermined amount of JP-4 leaked from an underground, 10-centimeter (4-inch) diameter fuel supply line and seeped into the ground near Landfill 1. The leak was discovered in 1965 during construction of an impact test facility at Landfill 1. The leak was repaired; however, subsequent excavations in the area have encountered fuel. Robins AFB began construction of new fuel storage tanks on the site of Landfill 1 during 1983, before the start of the IRP Phase II, Stage 2 field work. Prior to the start of construction, most of the contents of Landfill 1 were excavated and transported off the Base for redisposal. Construction workers at the site reported that they encountered fuel in the excavations. During the IRP Phase II activities, three wells were installed in an effort to determine the extent of the contamination. These wells, LF1-1, LF1-2, and LF1-3, also are shown in Figure B-1. Contamination in these wells ranged from none in well LF1-1 to floating product present in well LF1-3.

#### B. GEOLOGY AND HYDROLOGY

Robins Air Force Base is located on an alluvial terrace of the Ocmulgee River within the upper Coastal Plain Province. The site is bisected primarily by two lithologic units: Quaternary fluvial deposits and the Cretaceous Providence Sand. Average annual precipitation is approximately 127 centimeters (50 inches). The water table at Robins AFB is shallow with a depth of approximately 6 meters (20 feet) over the western portion of the Base; it decreases towards the east where it discharges into a swamp. Recharge for the area occurs west of the Base where the Providence Sand crops out. The primary regional aquifer of the area is the Cretaceous Sand aquifer (Reference 73).

#### C. METHODS USED

The JP-4 Spill Site was studied extensively using ground water sampling, active and passive soil gas analysis, electromagnetic induction, and resistivity. These methods and the rationale for choosing them are summarized in Table B-1.

Ground water samples were collected from the three existing wells. However, the capability of the soil gas sampling van to drive a probe to ground water at depths of 2 to 3 meters (7 to 10 feet) meant that ground water samples also could be collected at any location accessible by the van. This technique has not been validated against the traditional approach of sampling a purged well, but it was adequate for confirming the presence of contamination in ground water. Nine ground water samples were collected using the soil gas probe.

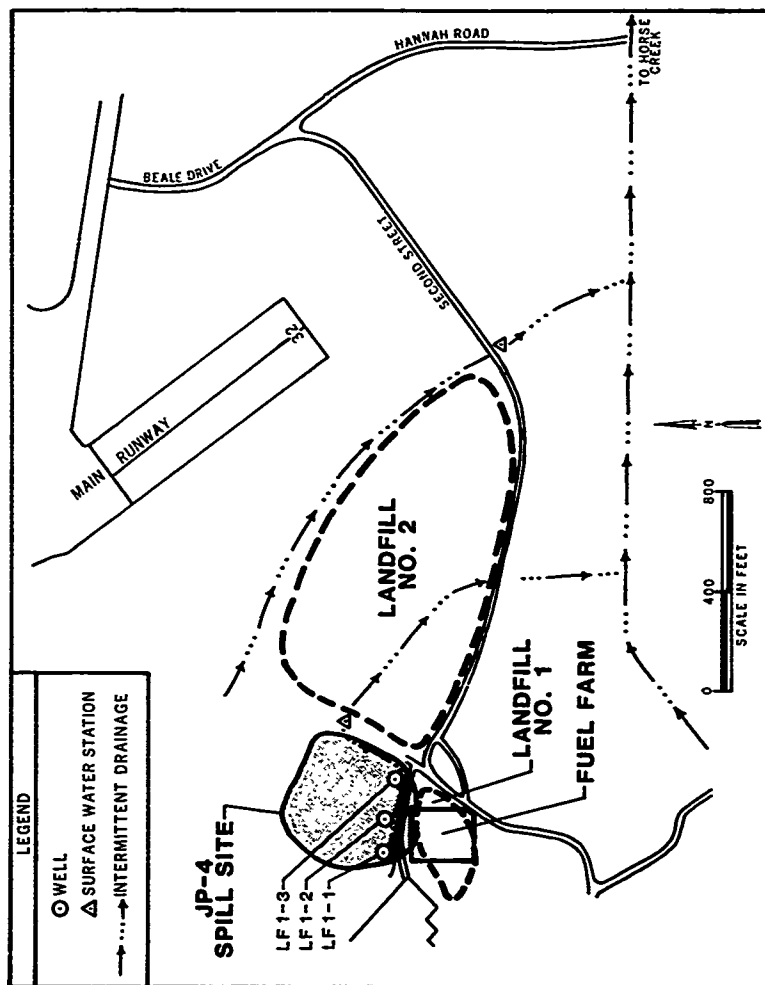


Figure B-1. JP-4 Spill Site, Fuel Farm, and Landfill 1 at Robins AFB.

TABLE B-1. MEASUREMENT TECHNIQUES USED AT THE JP-4 SPILL SITE, ROBINS AFB.

| Measurement; instrument   | Purpose   |
|---|---|
| Water samples; pump, tubing   | Collect ground water and floating product for analysis on site by GC used for soil-gas.                 |
| Water level, depth of floating product; metal tape  | Determine water level and depth and thickness of JP-4 floating product.                                 |
| Active soil gas sampling; Tracor Gas Chromatograph and Spectra Physics 4270 Computing Integrator on site      | Determine concentrations of organic compounds in soil gas.  |
| Passive soil gas sampling; 3M Industrial Hygiene Badges, 3400 Gas Chromatograph and integrator, in laboratory | Determine concentrations of organic compounds in soil gas; determine exposure times for expanded study. |
| Direct current resistivity, Wenner array; Bison Offset Sounding System  | Determine lateral and vertical changes in electrical resistivity.                                       |
| Electromagnetic Induction; Geonics EM-31, and EM-34   | Determine lateral and vertical changes in near-surface conductivity and locate buried metal pipes.      |

Two soil gas studies were performed at the JP-4 Spill Site, to allow comparison of the soil gas methods and to provide additional data for comparisons to the geophysical results. The initial locations chosen for the active soil gas sampling were based on information from the existing wells. An area of suspected high concentration was chosen first, followed by points chosen to establish the boundaries of the contaminated area. Emphasis was placed on the delineation of the contamination, rather than on colocating soil gas and ground water samples. However, some colocated samples were obtained. Duplicate soil gas samples were obtained at two locations. In addition, a profile of concentration with depth was developed, which led to the decision to use a deeper sampling depth. In summary, 13 soil gas samples were collected at a nominal depth of 1 meter (3 feet); 25 soil gas samples were collected at a nominal depth of 2 meters (6 feet).

A calibration test for passive soil gas sampling was conducted at the JP-4 Spill Site in August, 1986. The test consisted of exposing three sets of nine samplers each. Trial exposure times were 1, 2, and 3 days. The samplers were distributed in groups of 9, spaced at 15-meter (50-foot) intervals along the fence which is parallel to the line of monitoring wells. Within each group, the samplers were 0.6 meters (2 feet) apart. Although during the previous months there had been a severe drought and the ground was initially dry and

hard, during the week of the survey, there were intermittent, heavy rain storms. Many of the sampler locations became covered with puddled water during the week.

The geophysical techniques were used in an effort to directly detect the JP-4 contamination. Direct Current resistivity provided a method for doing detailed soundings, i.e., evaluations of resistivity with depth. The EM-31 and EM-34 instruments were used mostly for profiling, but soundings were also performed. The EM-31 was also used to locate pipelines and other buried metal objects. The geophysical survey was performed 3 months before the soil gas survey could be conducted. To assure that results from the geophysical and soil gas surveys would be comparable, a semipermanent survey grid was established and an EPA representative was present during both studies.

The locations of the survey lines where the geophysical measurements were performed are shown in Figure B-2 and summarized in Table B-2. The initial step in performing the surveys was to establish a grid extending from the uncontaminated area across a portion of the contaminated area. A laser theodolite was used to survey the locations. These lines were nominally 200 meters in length, spaced 10 meters apart. Measurement locations were marked with stakes at 10-meter intervals. A topographic map showing the relative change with respect to the base station, Line A, station 0, is presented in Figure B-3. A downward slope with an elevation drop of about 1.5 meters occurs from the northwest to the southeast portion of the survey area. A ditch is located in the southeast portion of the grid.

TABLE B-2. ELECTROMAGNETIC MEASUREMENTS AT THE JP-4 SPILL SITE, ROBINS AFB.

| LINE | EM-31    | EM-31      | EM-34              | EM-34              | EM-34            |
|------|----------|------------|--------------------|--------------------|------------------|
|      | Vertical | Horizontal | 20 m<br>Horizontal | 40 m<br>Horizontal | 40 m<br>Vertical |
| A    | yes      | yes        | yes                | yes                | yes              |
| B    | yes      | no         | no                 | no                 | no               |
| C    | yes      | no         | yes                | no                 | no               |
| D    | yes      | no         | no                 | no                 | no               |
| E    | yes      | no         | yes                | no                 | no               |

Direct Current resistivity measurements were performed at 18 locations over both the contaminated and uncontaminated areas. To make the measurements, the Wenner array was used with "a" spacings of 0.5, 1, 2, 4, 8, and 16 meters. These soundings were spaced along Lines A and D, from stations 10 to 130 and from stations 30 to 150, respectively; two soundings were also performed along Line C at stations 140 and 150. After a rainstorm, one sounding was repeated to provide information on the effects of the rain. This resulted in a total of

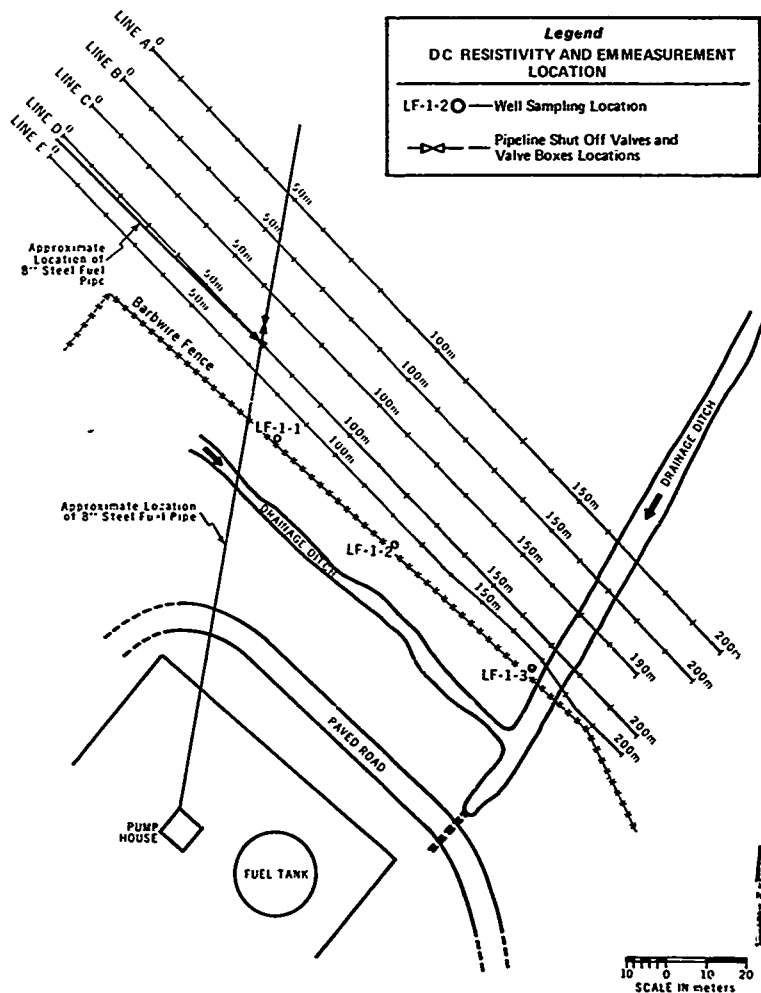


Figure B-2. Direct Current Resistivity and EM Measurement Locations at JP-4 Spill Site, Robins AFB.

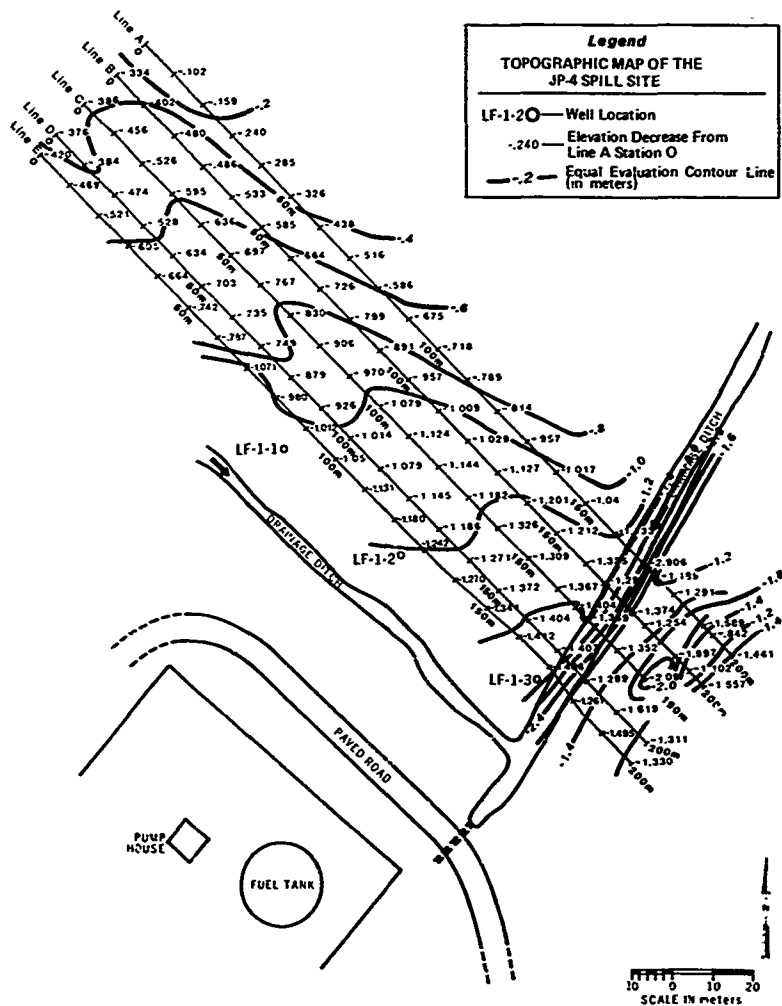


Figure B-3. Topographic Map of the JP-4 Spill Site Showing Relative Elevation Change (Meters) with Respect to the Base Station at Line A, Station 0 at JP-4 Spill Site, Robins AFB.



19 soundings. Each sounding required 30 to 45 minutes for one person to lay out the cables, pound in the stakes, connect the cables, make and record the measurements, and move to the next site. Calibration checks were performed at the beginning and end of each day of work.

EM measurements were selected to provide a rapid assessment of the sub-surface resistivity, and to delineate underground pipes and cables in the study area. This information was important to interpreting the resistivity results. Measurements with the EM instruments required one or two people. The EM-31 is fully portable for one person, while measurements with the EM-34 are most easily conducted with two people. To perform a series of EM-31 measurements using vertical dipoles along a 200-meter survey line, making measurements at 10-meter intervals, required approximately 30 minutes. To perform a series of EM-34 measurements using vertical and horizontal dipoles, along a 200-meter survey line, using a 20-meter coil spacing, and making measurements at 20-meter intervals, also required approximately 30 minutes.

Electromagnetic measurements with the EM-31 and EM-34 were initially obtained for Line A. For a given measurement, wide variations in the values were sometimes observed. It is believed this was due to interference from the base radar systems. The amount of the variation changed throughout the survey period and was more evident with the EM-34 instrument. Consequently, it was not possible to completely survey the area with the EM-34. Variations also were observed with the EM-31. However, they were generally less than 10 percent of the measured value. The maximum range and an average value were recorded for each station.

Initial EM-31 measurements along Line A were obtained with both horizontal and vertical dipoles at a height of 0.875 meters. Some measurements were also obtained with the EM transmitter-receiver oriented both parallel and perpendicular to the survey line. Plans called for obtaining measurements for the entire area with all four EM-31 combinations. This would have provided some depth and lateral homogeneity information. However, because of the radar interference and time constraints, most of the area was surveyed only with the vertical dipole and perpendicular orientation.

Field measurements were conducted during August and October 1986. The location of the contamination was assumed to be constant for the duration of the 3-month study. The geophysical measurements were conducted by a team from EMSL-LV with assistance from the U. S. Geological Survey. The soil gas measurements were performed on site by Tracer Research Corporation, Inc. Passive sampling using adsorbent charcoal badges for collection with analysis in the laboratory, was performed by LEMSCO.

#### D. GROUND WATER RESULTS

Water table elevations were measured at the three existing wells, but it was not possible to determine the ground water flow direction because the wells were installed in a straight line. The flow direction was assumed to be towards the swamp at the eastern edge of the study area.

Ground water samples were collected from the existing wells and by driving the soil gas sampling probe into ground water at selected locations. Ground water data for total hydrocarbons, benzene, and toluene are contoured in

Figures B-4 to B-6. In each of these figures, only the 1000  $\mu\text{g/L}$  contour line is marked. With the number of data available, the drawing of additional lines is not warranted. The contour lines have been left open towards the Fuel Farm enclosure. Permission was not obtained for digging in this area.

The general locations of the contamination indicated by the total hydrocarbons compared to the benzene and toluene are similar. Because of this similarity, it can be concluded that petroleum hydrocarbons are the only type of contamination present. The highest concentrations were measured at well LF1-3 and at a number of locations near the intersection of the two drainage ditches, where samples were collected using the soil gas probe. These locations are W-1, W-2, W-3, W-4, W-5, and W-6. The water sample for well LF1-3 was collected by sampling from below the floating product. At W-2 and W-4, the samples were not analyzed due to the presence of floating product. Values for these locations were assumed to be greater than 1000  $\mu\text{g/L}$  when preparing the contour plots.

The well LF1-1 is a one-point anomaly as the only location in the northwest part of the survey area with values above background. These values may be the result of cross contamination, an isolated surface spill, or ground water contamination. However, the presence of a 0.34 meter gradient away from well LF1-1 towards well LF1-3 suggests that the contamination identified in the area of well LF1-3 is not responsible for the contamination at well LF1-1. This is further verified by the clear delineation of the boundaries of the JP-4 spill on the north and west by other ground water and soil gas data.

## E. SOIL GAS RESULTS

### 1. Active Soil Gas Sampling Results

Figures B-7, B-8, and B-9 are contour maps for active sampling of soil gas concentrations of total hydrocarbons, benzene, and toluene, respectively. The general locations of the contamination indicated by the individual compounds are very similar, suggesting, as in the case of the ground water data, that the only type of contamination present is petroleum hydrocarbons. Data presented in these figures were obtained from nominal depths of 2 meters (6 feet). This depth was selected after an initial survey at nominal depths of 1 meter (3 feet).

The results of total hydrocarbons from the shallower survey are presented in Figure B-10. These data indicate two isolated areas of high concentrations while the deeper and more complete data indicate one large area. The extent and degree of contamination indicated by the two sets of data are substantially different. The shallower data set would lead to erroneous conclusions. Of particular interest is the comparison of the background value measured at SG-13 with sample collected immediately afterward at SG-14. This sample, at a depth of 2 meters (6 feet), and less than 2 meters away had a concentration of 280,000  $\mu\text{g/L}$ . A clay barrier was not evident in this area to explain the difference between the two values. This suggests that some sort of chemical, physical, or biological degradation of the soil gas vapor is taking place near the surface. Above this zone, concentrations are at background, while below it, the concentrations are substantially higher. Measurements of background concentrations apparently were valid at seven of the locations

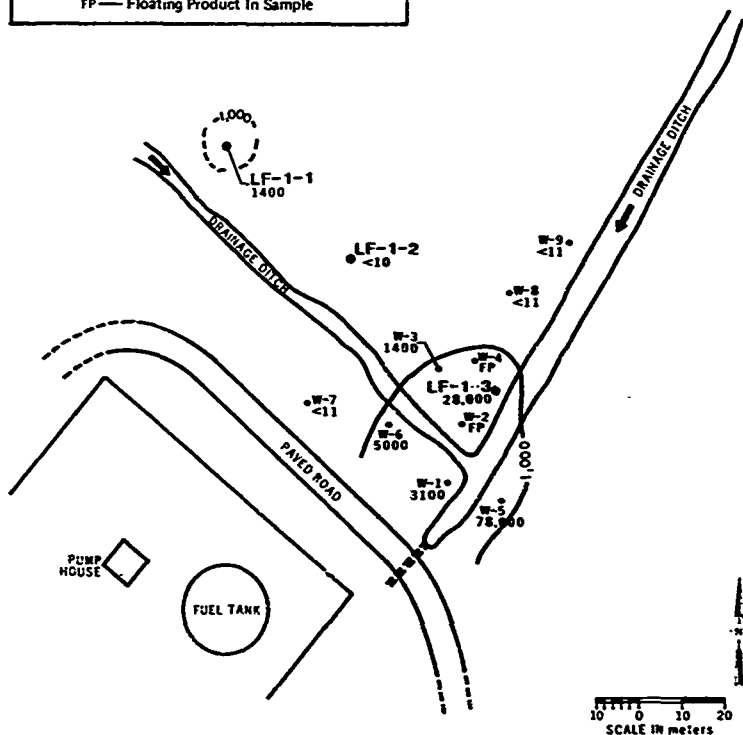
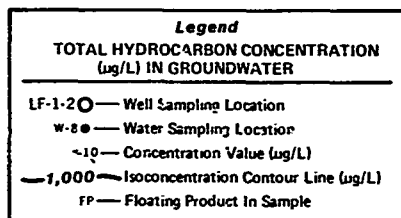


Figure B-4. Concentrations of Total Hydrocarbons in Ground Water at the JP-4 Spill Site, Robins AFB.

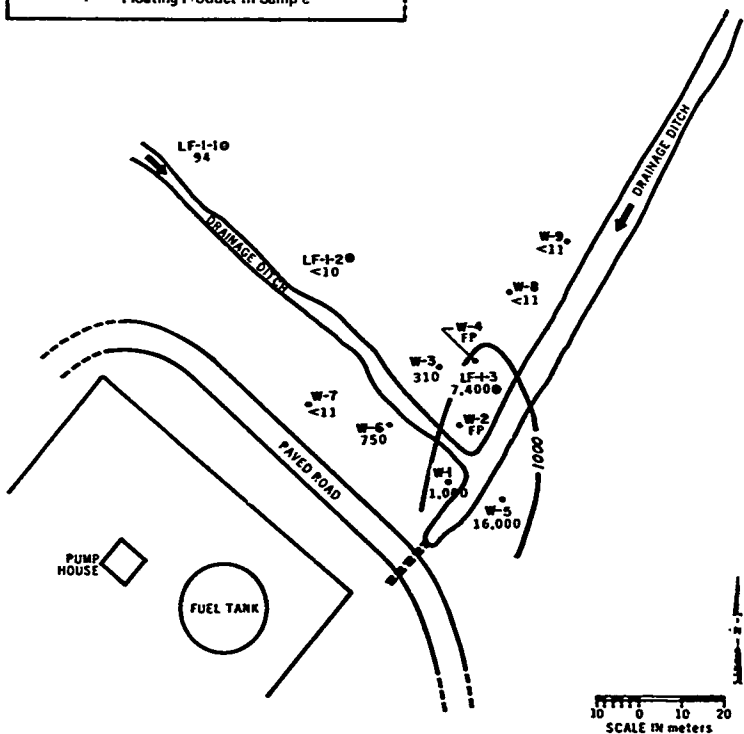
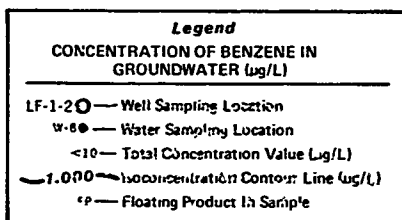


Figure B-5. Concentrations of Benzene in Ground Water at the JP-4 Spill Site, Robins AFB.

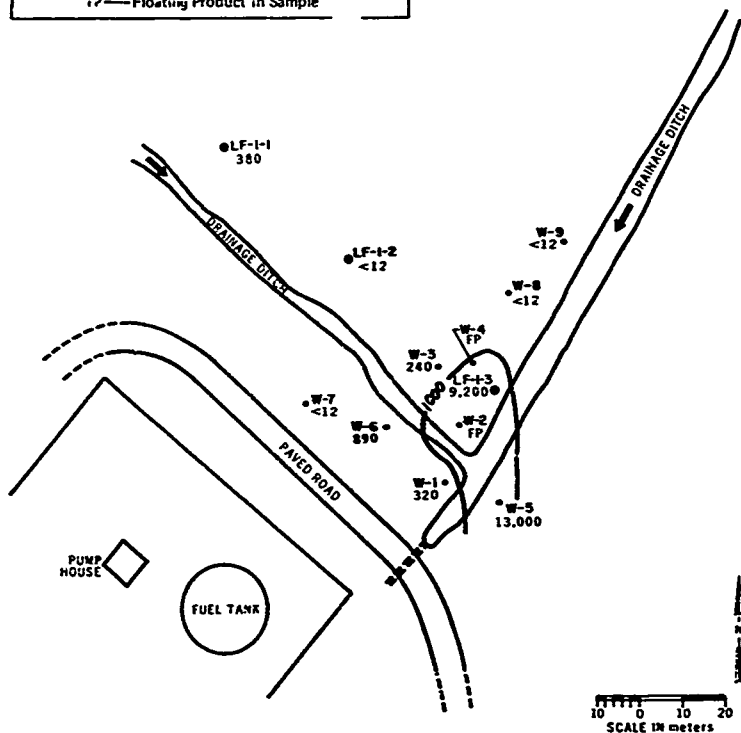
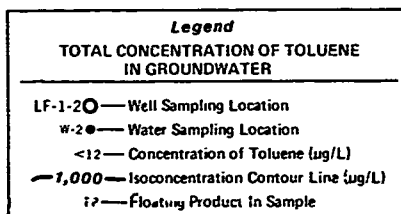


Figure B-6. Concentrations of Toluene in Ground Water at the JP-4 Spill Site, Robins AFB.

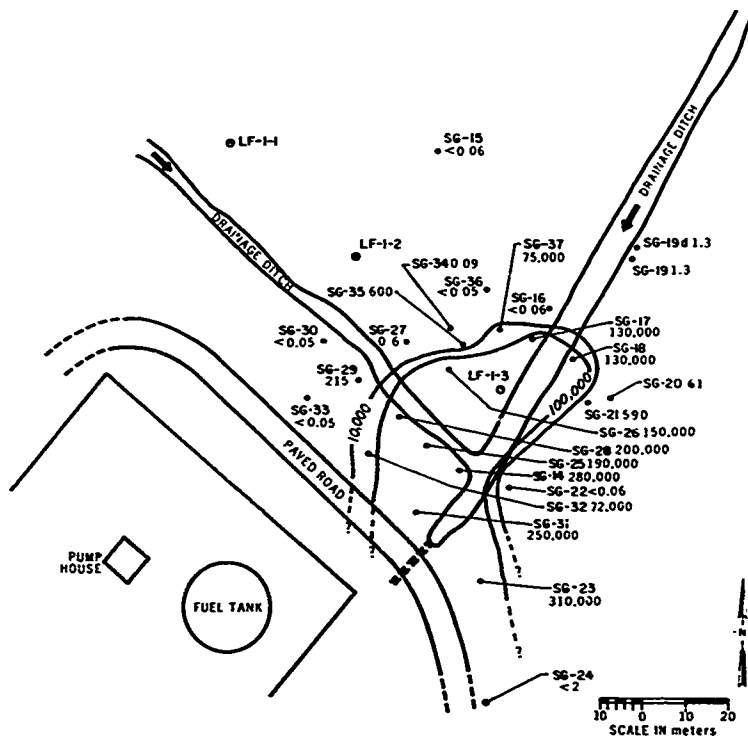
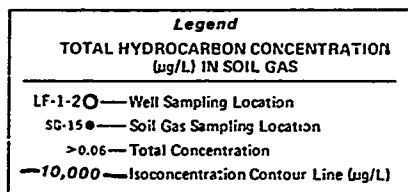


Figure 8-7. Concentrations of Total Hydrocarbons in Soil Gas at the JP-4 Spill Site, Robins AFB. Nominal 2-Meter (6-foot) Sampling Depth

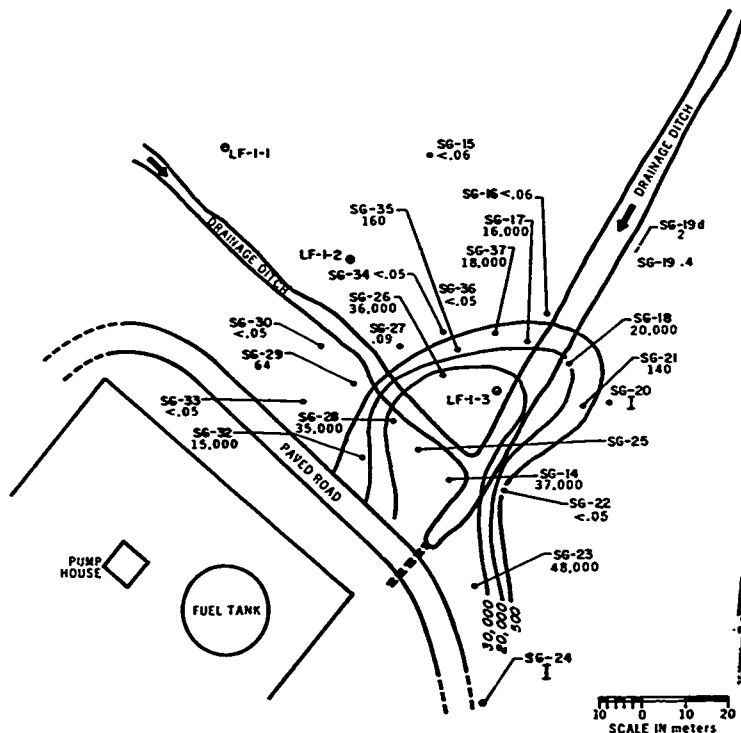
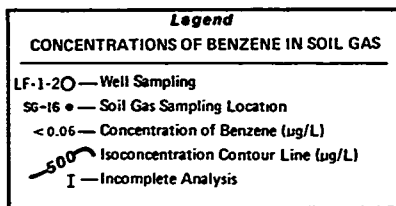


Figure B-8. Concentrations of Benzene in Soil Gas at the JP-4 Spill Site, Robins AFB. Maximal 2-Meter (6-foot) Sampling Depth

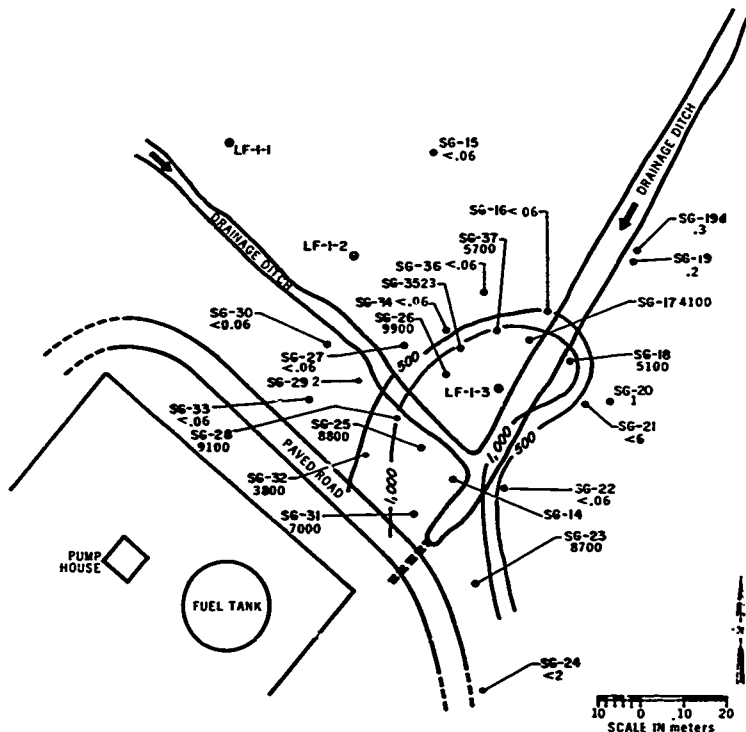
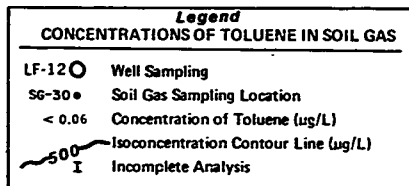


Figure B-9. Concentrations of Toluene in Soil Gas at the JP-4 Spill Site, Robins AFB. Nominal 2-Meter (6-foot) Sampling Depth



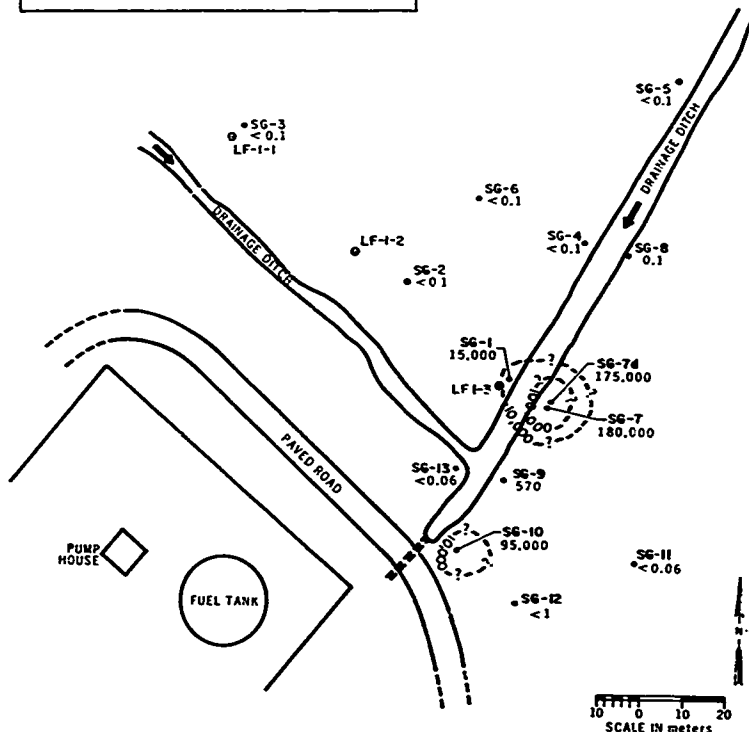
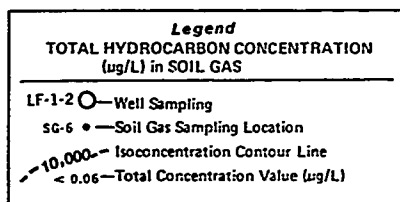


Figure B-10. Concentrations of Total Hydrocarbons in Soil Gas at the JP-4 Spill Site, Robins AFB. Nominal 1-Meter (3-foot) Sampling Depth

surveyed at the shallower depth. However, at the other locations where comparisons were possible, the shallower concentrations were generally less. This emphasizes the importance of performing a series of soil gas measurements at several depths to select an optimum depth for the sampling, at the outset of a study.

Normally, VOCs are present in JP-4 in sufficient quantity to be detected in soil gas. However, the original JP-4 spill occurred in 1965, and the 20 years which passed allowed ample opportunity for the VOCs to vaporize or degrade. This might have resulted in negative results from the soil gas study although the less volatile components of organic contamination were present. However, VOCs were present in the soil gas; the technique was successful in delineating the contamination. The age of the spill may be responsible for the large changes in concentration with depth since a population of hydrocarbon-consuming microorganisms would have had time to become well established.

To compare the soil gas results to the ground water data, a circle plot was prepared, shown in Figure B-11. Two circles were placed next to eight paired soil gas and ground water sample locations. To qualify as a pair, the two samples had to have been collected within 5 meters of each other. The upper circle represents the soil gas concentration and the lower circle represents the ground water concentration. The circles were darkened to represent cases when the concentrations of total hydrocarbons in soil gas or ground water were greater than background, and left blank to represent background concentrations. Of the eight pairs, six showed agreement. The two cases which did not match both had ground water contamination with background-level soil gas concentrations. At well LFI-1, this may be due to the shallow sampling depth. However, at water sampling point W-5, the nearest soil gas sample, SG-22, was collected at the deeper depth, so this is not a possibility. The difference may be due to variations in subsurface permeability. Overall, the soil gas results compared favorably with the ground water data, successfully delineating the organic contamination.

## 2. Passive Soil Gas Sampling Results

A number of problems were encountered during the analyses of the extracts from the passive samplers. During the initial desorption of the badges, contaminated carbon disulfide solvent was used. This precluded quantitative interpretation of the data from the six badges affected. Methanol was tried as a solvent but it also proved to be contaminated; one sample was affected. Solvent from a different batch of carbon disulfide was procured and the analyses proceeded. Of the remaining badges, two were not analyzed for a number of reasons including spillage, or the badge arriving unsealed; 17 had no detectable contamination; and one had detectable contamination. For these reasons, results are presented qualitatively.

In the qualitative presentations, the data are classified into several categories. These categories are listed below:

- background concentration, using clean solvent;
- above background concentration, using clean solvent;
- background concentration, using contaminated solvent;
- above background concentration, using contaminated solvent; and
- not analyzed.

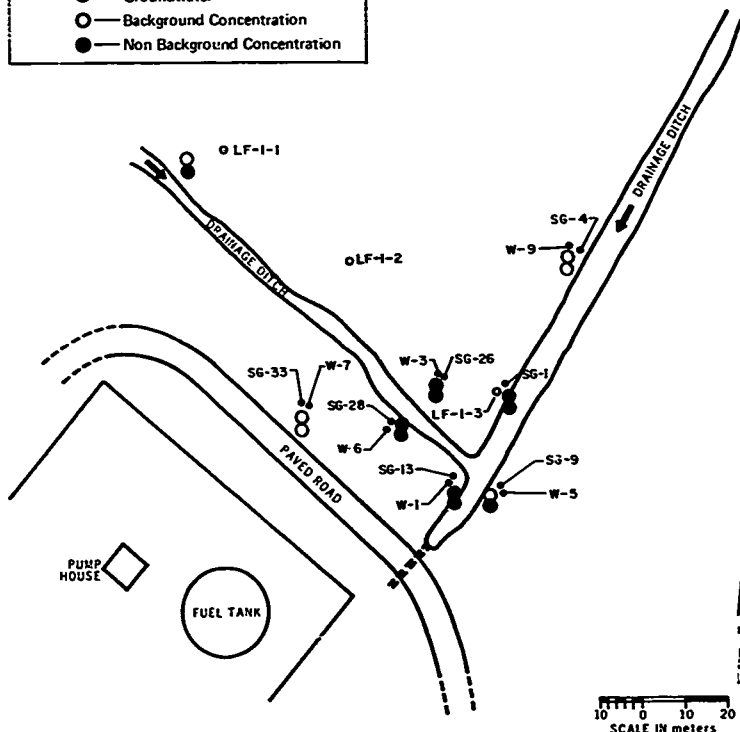
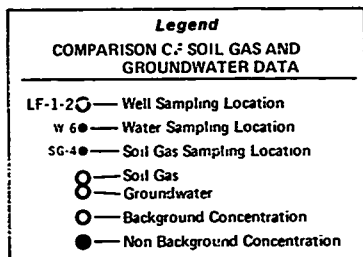


Figure B-11. Comparison of Soil Gas and Ground Water Data at the JP-4 Spill Site, Robins AFB.

It was possible to determine that a badge desorbed with impure solvent was contaminated if the peak areas on the chromatogram were substantially greater and more numerous than those for the solvent chromatogram. This approach would not detect minor amounts of contamination on the badge. However, the use of these categories makes it possible to draw some conclusions about the effectiveness and potential for passive soil gas sampling at the JP-4 Spill Site at Robins AFB.

In Figure B-12, locations of the three installations of badges at the JP-4 Spill Site are shown in relation to the results from the ground water and soil gas investigations. The badges in group D were located between well LF1-3 and ground water sample point W-2. At both these locations, floating product was present in the ground water samples; soil gas concentrations were also high in the area, generally above 100,000  $\mu\text{g/L}$ . For these reasons, the badges in group D are believed to have been located above floating product.

Group E is located 15.2 meters to the northwest of group D. The entire nine-badge array was within a distance of 2 meters of ground water sampling point V-3 which had a total hydrocarbon concentration of 1,400  $\mu\text{g/L}$ . The array was near and towards the outside edge of the isoconcentration contours for both 1,000  $\mu\text{g/L}$  total hydrocarbons in ground water and 10,000  $\mu\text{g/L}$  total hydrocarbons in soil gas. Since the boundaries between contaminated and uncontaminated soil gas and ground water have been observed to be very distinct, it cannot be concluded with finality that group E was located over contaminated ground water. However, the presence of contamination at W-3 suggests this was likely.

Group F was located 30.4 meters to the northwest of group D. Based on nearby soil gas sampling points SG-27 and SG-34, and well LF1-2, this area was uncontaminated.

Figure B-13 displays the results for each of the arrays. Array D, located over the floating product, had six contaminated badges and two uncontaminated badges. The badges had detectable contamination for all three exposure periods; the uncontaminated badges occurred for the 1- and 2-day exposure periods. This suggests that a 3-day exposure period would be the best choice for further sampling. Array E had no detectable contamination for any of the badges. This may be due to a number of reasons including a less contaminated sampling location than expected, the shallow installation of the samplers, inhomogeneities in the permeability of the soil, inadequate exposure time, or some combination of these. For example, physical or biological degradation may be causing soil gas concentrations to decline near the surface. The shallow installation may have resulted in the samplers being located above the zone of contaminated soil gas. During the active soil gas survey, anomalously low concentrations were measured at depths of 1 meter compared to depths of 2 meters, suggesting that this may be a significant factor. If exposure time is a factor, times longer than 3 days may be warranted. Array F had no detectable contamination present in the area; this is consistent with the ground water and soil gas data. Based on this information, additional surveys might be conducted successfully using exposure times of 3 days. It would be desirable to conduct tests for 4- and 5-day exposure times and to perform a series of depth profiles to determine if the 0.3-meter installation depth should be increased.

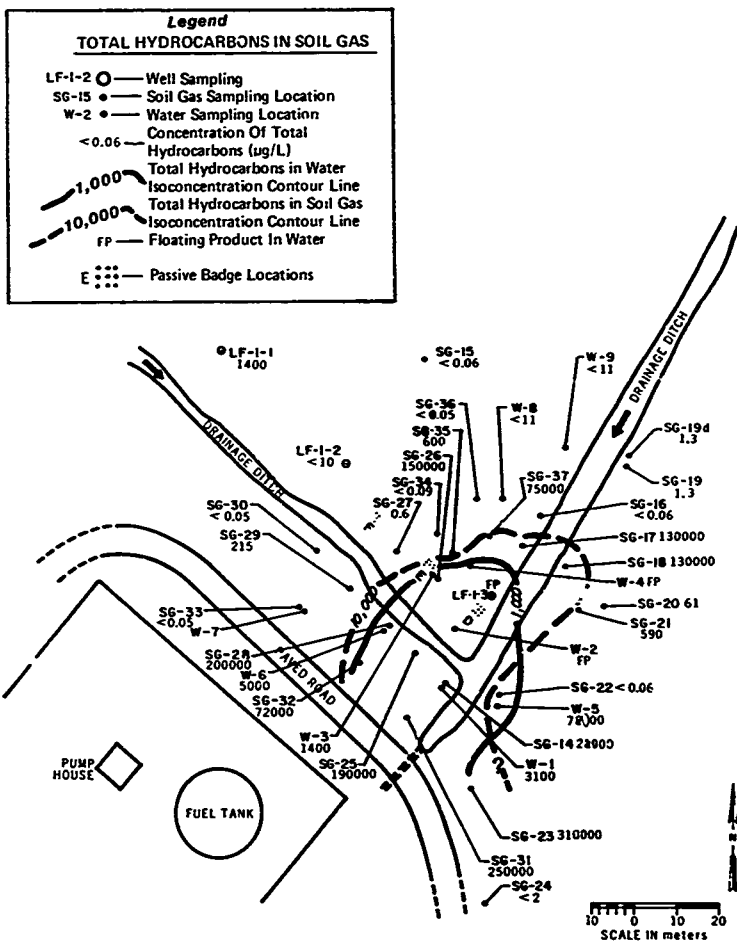


Figure B-12. Location of Passive Samplers in Relation to Ground Water and Active Soil Gas Data at JP-4 Spill Site, Robins AFB.

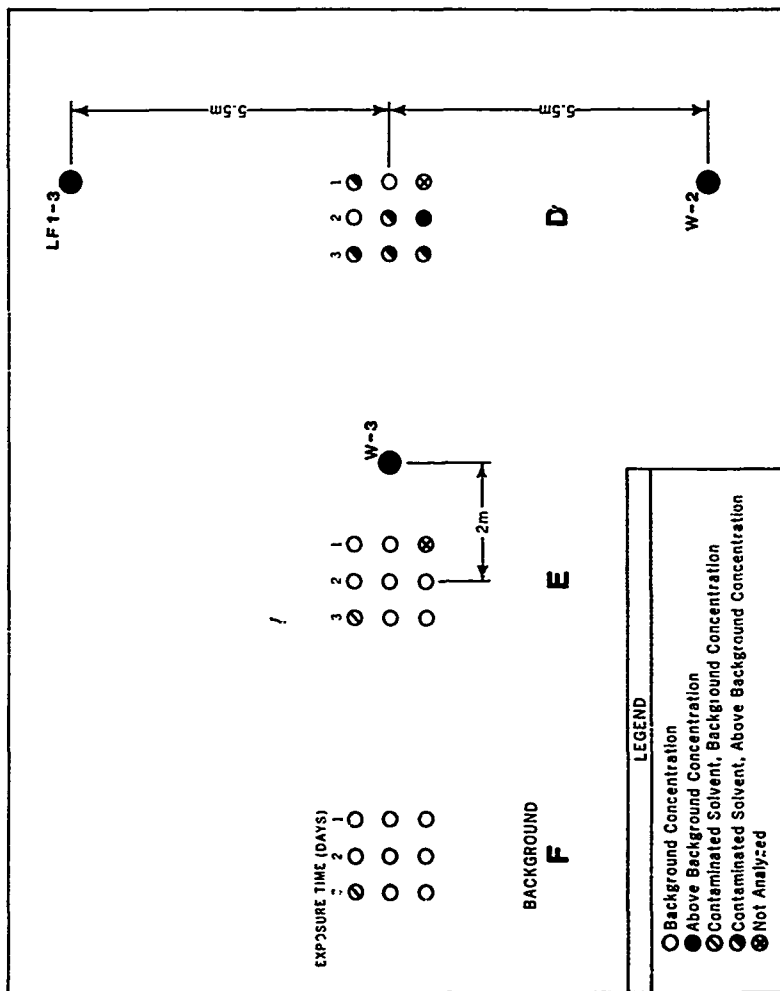


Figure B-13. Passive Sampler Results for the JP-4 Spill Site, Robins AFB.

In summary, the results for the passive soil gas technique show some agreement with the ground water and soil gas data. However, at this location, some badges did not detect contamination when it was believed to be present. The potential for false negatives in these cases causes serious concern over the use of this technique. These results emphasize the importance of performing a preliminary study, to determine suitable exposure times and sampling depths, evaluate natural variability, and to refine analytical procedures. Within this context, it may be possible to rely on the passive soil gas technique for consistent results. Further testing of the performance of this technique is recommended before it is used routinely. Because of its low cost, this technique has potential for reducing site investigation costs.

## F. GEOPHYSICAL RESULTS

The results of the EM surveys will be presented first, followed by the results of the direct current resistivity surveys. Conductivities measured by the EM instruments have been converted to resistivities so the data have a common format. (Resistivity is the reciprocal of conductivity.) Figure B-14 shows the location of the geophysical survey lines in relation to the location of the 50,000 µg/L contour line for total hydrocarbons in soil gas. The positions of the three monitoring wells (LF1-1 to LF1-3) and some of the water sampling points are also indicated for reference. The contamination is present at the extreme southeast end of the survey grid. In addition to the high soil gas values, pure JP-4 fuel was observed in well LF1-3, and at water sampling points W-4 and W-2 around Line E, stations 160 to 170. The depth of the fuel was approximately 0.5 meters.

EM results are shown as contoured apparent resistivity data in Figure B-15. In the northwest portion of the survey area, the EM results were dominated by the presence of buried pipelines. This is seen in Lines A to E, Stations 30 to 80, and along Line D, Stations 0 to 80. The location of these pipelines was not known at the time of the survey. In addition to these effects, the grounded barbed wire fence may have influenced the EM response along the southern portion of Line E, Stations 140 to 190. In the southeast portion of the survey area, from Line A at Station 185 to Line E at Station 200, low resistivity values less than 64 ohm meters were observed. These probably reflect the presence of the landfill in that area. No correlation is evident between the presence of JP-4 fuel in the subsurface and the EM apparent resistivity data in this figure.

Direct Current resistivity soundings were conducted along Line A, from stations 10 to 130; along Line C, at Stations 140 and 150; and along Line D from stations 30 to 150. The pseudosections are shown in Figures B-16 to B-18. Apparent resistivity variations from 189 to over 2000 ohm meters were observed throughout the area, in both the contaminated and uncontaminated portions. The lateral variations around Line A, Station 50, probably were due to the trench collocated with the buried pipeline. Other lateral variations, from 800 to over 2000 ohm meters, were observed along Line A from Stations 90 to 130. Since the active soil gas survey did not indicate any significant contamination in this area, these variations were attributed to the natural properties of the subsurface. Similar results were observed along Line D. The southeastern portion of Line D, Station 150, was at the edge of the contaminated area, as designated by the soil gas and ground water data. The larger electrode separation distances went to the edge of the drainage ditch, in the middle of the contaminated area.

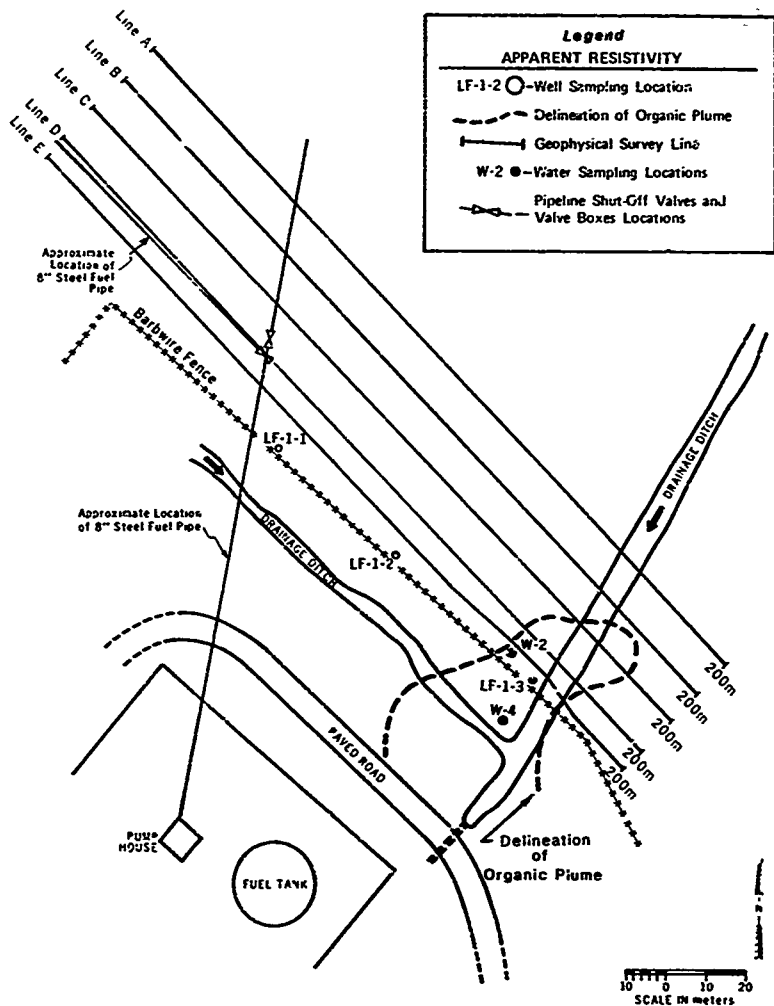


Figure B-14. Geophysical Surveys in Relation to the Organic Contamination Indicated by the Ground Water and Soil Gas Data at the JP-4 Spill Site, PAFB.



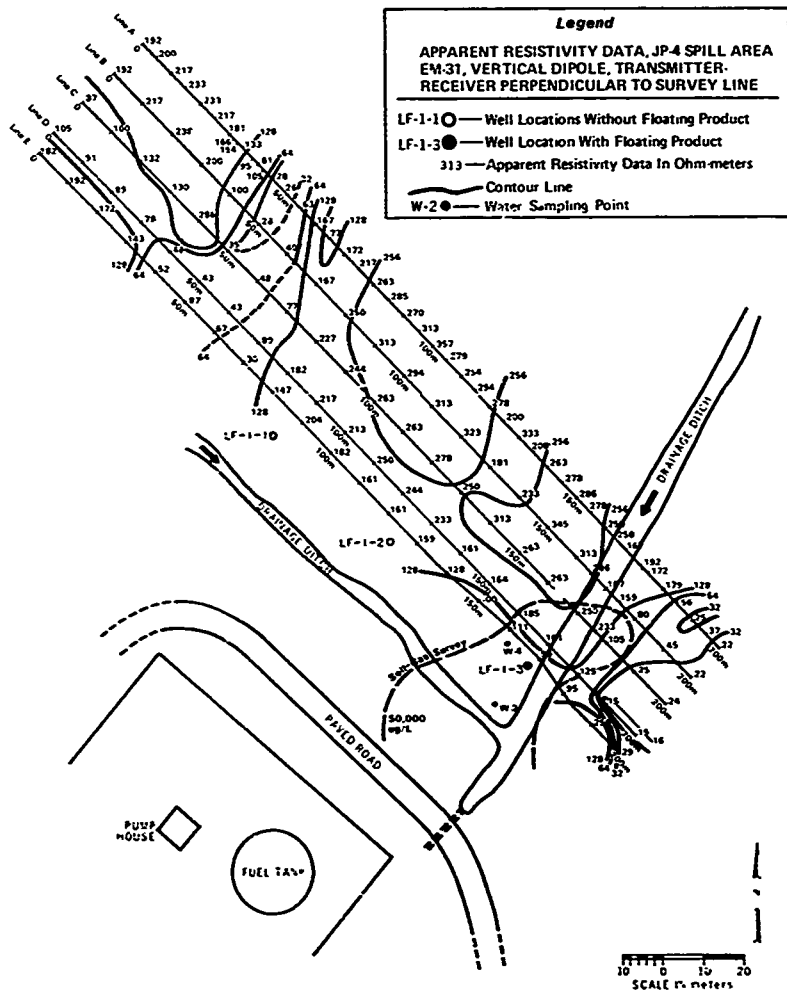


Figure 8-15. EM-31 Vertical Dipole Data, with Instrument Oriented Perpendicular to the Survey Line at the JP-4 Spill Site, Robins AFB.

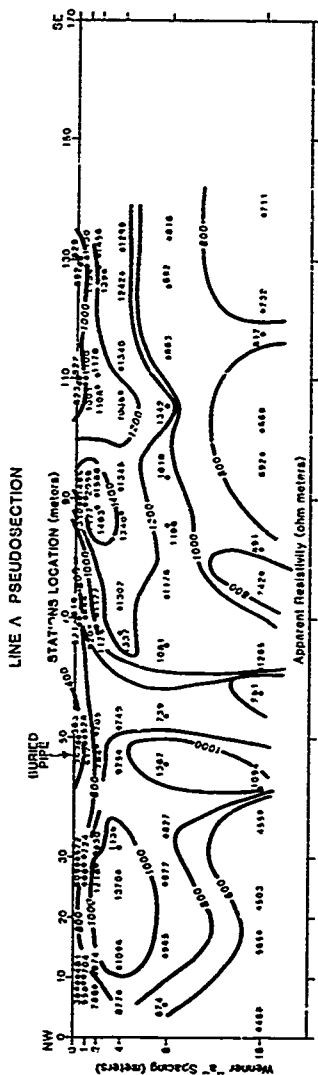


Figure B-16. Apparent Resistivity Pseudosection for Line A, JP-4 Spill Site, Robins AFB.

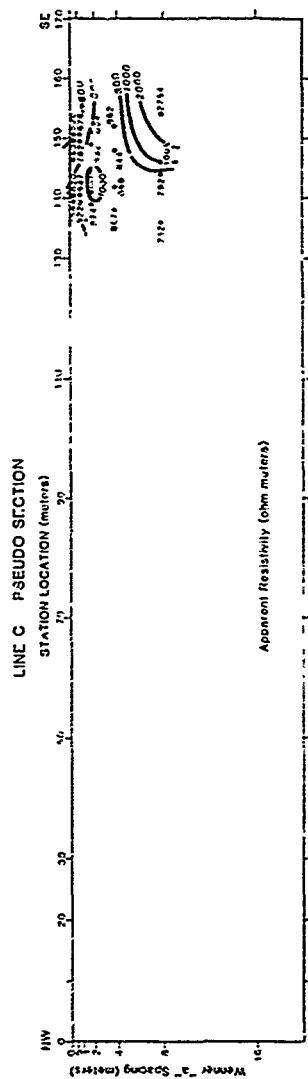


Figure B-17. Apparent Resistivity Pseudosection for Line C, JP-4 Spill Site, Robins AFB.



There does not appear to be any correlation between the presence of JP-4 fuel in the subsurface and the dc apparent resistivity data shown in the pseudo-sections.

The apparent resistivity data were interpreted with one-dimensional model inversions. An example of a model and a comparison of actual and predicted data from the model for Line A, Station 10, is shown in Figure B-19. At this station, an EM sounding also was obtained. The EM-31 data were interpreted and a comparison with the measured data is presented in Table B-3. The resulting model is included in Figure B-19. There is reasonable agreement between the two models. They indicate three to four layers of resistivity in the top 10 meters of the subsurface. The depth to the water table of 3.7 meters is indicated on the figure. This was measured in Well LF1-3 in October 1986, and corrected for the elevation change to this station from the grid origin. There is good agreement between this depth and the decrease in the resistivity model from 1400 to 300 ohm meters at a depth of 3.4 meters.

TABLE B-3. EM MEASURED AND CALCULATED DATA: LINE A, STATION 10, JP-4 SPILL SITE, ROBINS AFB.

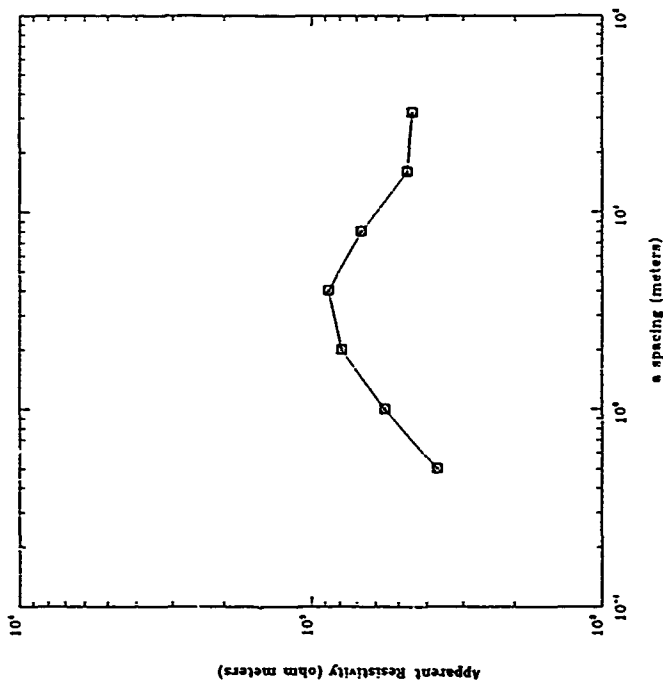
| EM-31<br>height<br>meters | Dipole<br>orientation | Measured<br>apparent<br>resistivity<br>ohm meters | Calculated<br>apparent<br>resistivity<br>ohm meters |
|---------------------------|-----------------------|---|---|
| 0.08                      | Vertical              | 200   | 191   |
| 0.88                      | Vertical              | 208   | 217   |
| 2.05                      | Vertical              | 278   | 284   |
| 0.08                      | Horizontal            | 286   | 249   |
| 0.88                      | Horizontal            | 333   | 347   |
| 2.05                      | Horizontal            | 500   | 518   |

#### One dimensional inversion model, 3 layers

|         |                               |                        |
|---------|-------------------------------|------------------------|
| Layer 1 | Resistivity = 159 ohm meters  | Thickness = 0.4 meters |
| Layer 2 | Resistivity = 2703 ohm meters | Thickness = 2.5 meters |
| Layer 3 | Resistivity = 92 ohm meters   |                        |

To see the effect of precipitation on the electrical measurements, a resistivity sounding for Line D, station 130, was repeated following a rainstorm. On August 20 and 21, 1986, a total of 6.43 centimeters (2.53 inches) of precipitation was reported at the site. No rainfall had fallen in the previous 5 days before the survey. The first set of measurements was performed on August 21 at 14:35 local time. The heavy rainfall started about 17:00 and 3.4 centimeters (1.35 inches) fell in a period of about 3 hours. The measurements were repeated the following morning, August 22 at 09:30, about 13 hours after the rain stopped. The same electrode holes were used in both sets of readings. The results are presented in Figure B-20. A 20 percent decrease is observed in the near surface apparent resistivity measurements. This occurs out to an electrode spacing of

Line A, Station 10 NW



□ Measured D C Data  
— Calculated D C Model Data

D C Resistivity Model

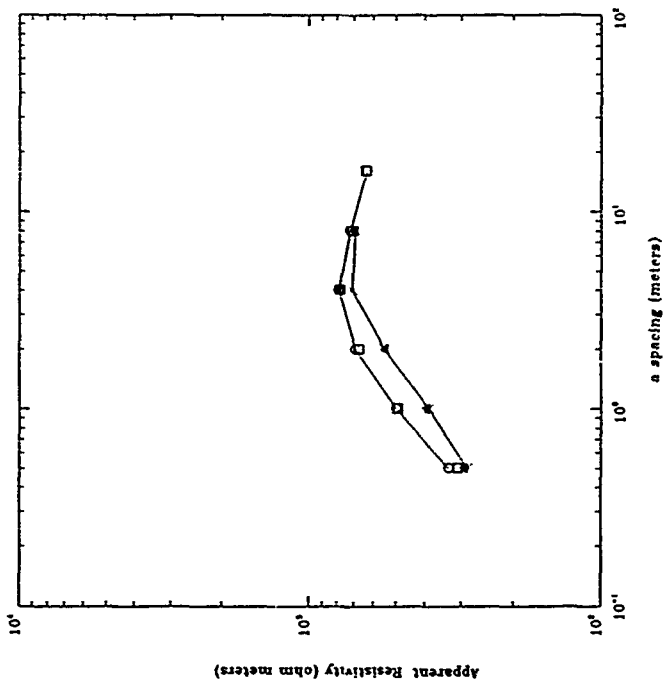
|                   |                  |
|-------------------|------------------|
| $\rho_1 = 362.9$  | $\rho_2 = 0.4$ m |
| $\rho_3 = 1377.0$ | $\rho_4 = 3.0$ m |
| $\rho_5 = 289.5$  | $\rho_6 = 5.1$ m |
| $\rho_7 = 468.1$  | ohm meter        |

EM-31 Resistivity Model

|                   |                  |
|-------------------|------------------|
| $\rho_1 = 159.0$  | $\rho_2 = 0.4$ m |
| $\rho_3 = 2703.0$ | $\rho_4 = 2.5$ m |
| $\rho_5 = 92.0$   | ohm meter        |

Figure 8-19. Model Results and Comparison of Measured and Calculated dc Resistivity and EM-31 Data for Line A, Station 10 at the JP-4 Spill Site, Robins AFB.

Line D, Station 130SE



□ measured data, before rain  
 ○ measured data, after rain  
 — calculated data, before rain  
 — calculated data, after rain

Layered model, before rain

$\rho_1 = 148.5$  ,  $h_1 = 0.2$  m

$\rho_2 = 740.8$  ,  $h_2 = 0.9$  m

$\rho_3 = 2075.9$  ,  $h_3 = 0.8$  m

$\rho_4 = 596.7$  ohm meter

Layered model, after rain

$\rho_1 = 161.1$  ,  $h_1 = 0.2$  m

$\rho_2 = 407.2$  ,  $h_2 = 1.1$  m

$\rho_3 = 2817.8$  ,  $h_3 = 1.0$  m

$\rho_4 = 475.9$  ohm meter

Figure B-20. Comparison of dc Resistivity Sounding Results Before and After a Rainstorm on August 21, 1986 at the JP-4 Spill Site, Robins AFB.

2 meters. The interpreted models indicate a decrease in the resistivity of the second layer from 740 to 407 ohm meters, a 48 percent decrease in intrinsic resistivity. This layer is 0.2 to 1.1 meters in depth. This decreased resistivity is probably due to an increase in the water saturation of this zone. These results provide a lower bound on the detection limit for the presence of JP-4 in the present survey. Thus, JP-4 contamination could not be detected unless the resistivity contrast of the JP-4 with the surrounding formation was greater than that provided by these rainfall events.

One-dimensional model calculations were performed for the dc resistivity data; the model results agree fairly well with the observed data. Poor results were observed for Line A, Stations 50, 70, 90, and 110; Line C, Station 150; and Line D, Station 140. These poor fits were probably due to lateral resistivity variations and indicate that two-dimensional modeling may be required to further interpret the data. The interpreted cross sections of the resistivity along Lines A, C, and D are shown in Figures 8-21 to 8-23. The results are plotted with a ten-to-one vertical exaggeration. Four layers were observed over most of the area. A fairly high resistivity layer, 1000 to over 2000 ohm meters, was observed at depths ranging from about 1 to 2 meters along Line D and from about 0.4 to 5 meters along Line A. These features are in uncontaminated areas at the same depth as the zone of JP-4 fuel observed in the wells at the southeast portion of the survey area. It was not possible to find any published information on the electrical resistivity properties of the JP-4 fuel. It is also not known how the fuel might react with various geological formations. Therefore, it was not initially possible to attribute any change in resistivity of this layer to contamination with JP-4 fuel.

To obtain a better understanding of the electrical properties of JP-4 fuel, a simple laboratory experiment was conducted. These tests were designed to detect changes in resistivities to order of magnitude only. First, indirect measurements suggested that the resistivity of pure JP-4 is probably greater than 54,000 ohm meters. Then a container filled with undersaturated, fine-grained sand was prepared for further tests. The electrical resistivity values for the case with and the case without the JP-4 fuel were determined using a miniature resistivity array probe. The range of values for the two cases overlapped. If the lowest resistivity values for the two cases are selected, a resistivity increase of 10 to 46 percent may be attributed to the presence of the JP-4 fuel. These numbers should be used with caution, however, since there is no guarantee that the lowest possible resistivity value for each case was measured. These results suggest that even though the JP-4 fuel may be 760 times (76,000 percent) more resistive than the water electrolyte, the change in resistivity of an undersaturated formation may be less than 100 percent when the JP-4 is added. Since the naturally occurring resistivity variations at Robins AFB are on the order of 100 percent, as shown in Figures 8-21 to 8-23, it is questionable whether any JP-4 contamination could be detected clearly with dc electrical resistivity measurements at this study site.

These simple laboratory tests were conducted with clean, fine-grained sand. How the JP-4 would interact other geological formations, in particular those including clay, should be addressed in future research efforts. Tests using core samples from selected bases could be conducted to determine the properties of JP-4 in various geological formations. This would aid in understanding what conditions are necessary for the detection of subsurface organics using geophysical techniques.





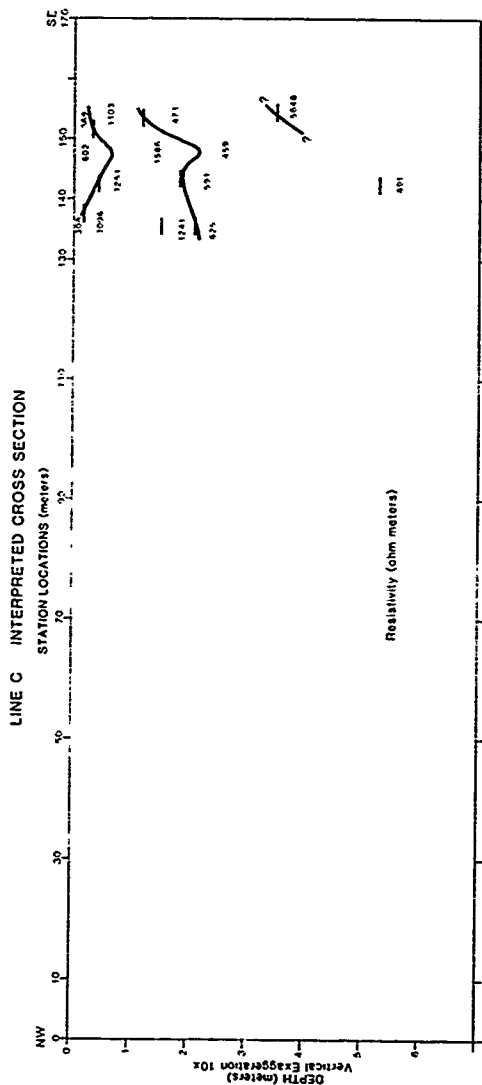


Figure 8-22. Interpreted dc Resistivity Cross Section for Line C, JP-4 Sp11 Site at Robins AFB.

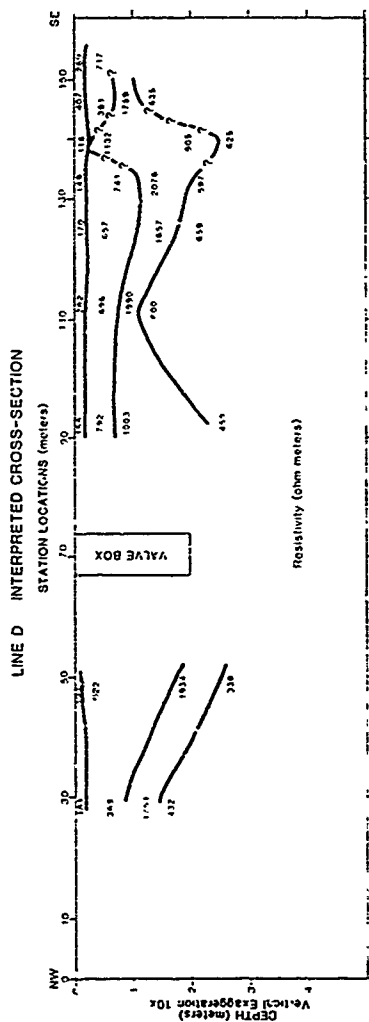


Figure B-23. Interpreted dc Resistivity Cross Section for Line D, JP-4 Spill Site at Robins AFB.

## G. SUMMARY

To summarize, active soil gas data compared favorably with the ground water data. Active soil gas samples collected at depths of 1 meter (3 feet) compared to those collected at 2 meters (6 feet) showed substantially different contamination. This emphasizes the importance of performing a depth profile at the beginning of a study to select the optimum sampling depth. Otherwise, erroneous conclusions may result. The passive soil gas results were mixed; results in two of the three areas tested agreed with the ground water data. However, in the third area with intermediate concentrations, the passive soil gas sampling did not detect contamination which nearby ground water and active soil gas data indicated was present. This could have been due to the shallow sampling depth, an inadequate exposure time, or a sampling location outside the contamination. These results emphasize the importance of performing a preliminary study, to determine suitable exposure times and sampling depths, evaluate natural variability, and to refine analytical procedures. Within this context, it may be possible to rely on the passive soil gas technique for consistent results. Further testing of the performance of this technique is recommended before it is used routinely. Because of its low cost, this technique has potential for reducing site investigation costs in some cases.

Neither the dc resistivity or EM detected the contamination. The resistivity features identified were attributed to the natural geological variability, the variability which resulted from the rainfall, and the lack of resistivity contrast between the JP-4 contamination and the surrounding formation. Rudimentary laboratory experiments established estimates that the increase in resistivity caused by adding JP-4 to a clean, fine-grained unsaturated sand was substantially less than natural variations of resistivity in the soil at Robins AFB.

## APPENDIX C

### TINKER AFB

#### A. BACKGROUND

Tinker AFB is located in central Oklahoma, within the corporate limits of Oklahoma City and adjoining the suburbs of Midwest City and Del City. A lens of JP-4 fuel has been identified at Fuel Farm 290. This lens is the focus of this investigation and is believed to be caused by leaks from corroding tanks. Fuel Farm 290 consists of a 3-acre fenced area at the far northern section of the base, west of the runway. The fuel farm was activated in 1938 with the installation of five 81,828-liter (18,000-gallon) tanks. Through subsequent additions of 113,650-liter (25,000-gallon) Underground Storage Tanks (USTs), the fuel farm reached its present size of 25 USTs in the early 1940s and has been in active use since that time. The locations of these tanks also are shown in Figure C-1.

#### B. GEOLOGY AND HYDROLOGY

Tinker AFB is located within the Central Redbed Plains section of the Central Lowland Physiographic Province. The area encompassing the installation is characterized by gently rolling hills, broad flat plains, and well-entrenched main streams. The surface of the base is transected by two Permian lithologic units; the majority of the base, including the Fuel Farm 290 study area, is underlain by the Hennessey Group, consisting of the Fairmont Shale and Kingman Siltstone. The fuel farm is underlain by the Fairmont shale, which consists of flat-lying shales and sandstones. The far eastern portion of the base is underlain by the Garber Sandstone. The tanks are in an area with 10 to 20 feet of unconsolidated quaternary alluvium underlain by flat-lying shales and sandstones. They are buried 2 meters (6 feet) below the surface within the quaternary alluvium, which consists of unconsolidated and interfingering lenses of sand, silt, clay, and gravels (Reference 74).

Annual precipitation averages 81 centimeters (32 inches). The regional water table is at a depth of approximately 18 meters (60 feet), and a perched water table occurs within the alluvium around the tanks at a depth of about 2.4 meters (8 feet). The ground water at the fuel farm generally moves to the north east. The leaked JP-4 fuel occurs as a lens of free product floating on the perched water table in the north-central part of the site.

#### C. METHODS USED

The measurements conducted at the Tinker AFB Fuel Farm focused on the mapping of the JP-4 plume using soil gas sampling techniques and on obtaining ground water data for comparison to the soil-gas data. Electrical geophysical techniques were not used because of the abundance of metal objects including fences, railroad tracks, and buried tanks, pipelines, and power lines.

The first soil gas study, conducted in September 1986, was an attempt to map the plume by using a passive sampling technique. The passive soil gas field test consisted of the placement of 36 samplers in manifolds. These manifolds were deployed in pairs to allow comparison of results for two different

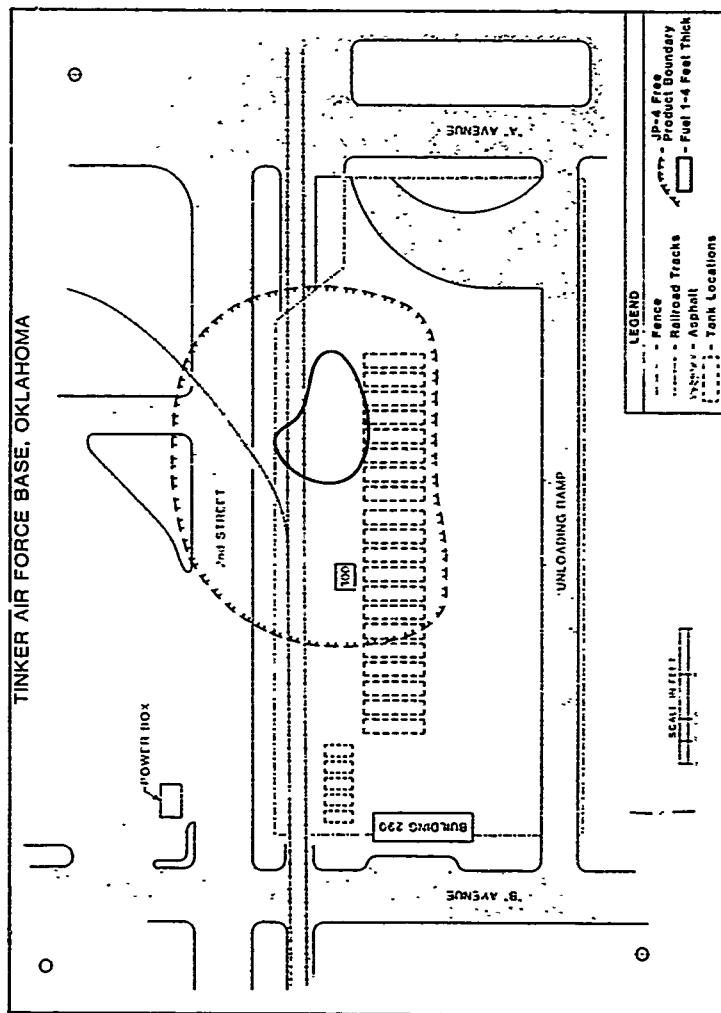


Figure C-1. Fuel Farm 290 at Tinker AFB.

1 meter (3 feet) away from and on opposite sides of the existing monitoring wells, in anticipation of the second part of the study when ground water samples would be collected from the wells for comparison purposes. Figure C-2 shows the sampler locations in relation to the monitoring wells. At two wells, two pairs of samplers were used to provide an estimate of sampling variability (B-07 and B-08; B-17 and B-18, respectively). Sampler pair B-14 was placed midway between two wells because it was not possible to dig a 0.3-meter (1-foot) hole in the highly compacted soil between the railroad tracks. In comparing the sampler locations with the lens of free product shown in Figure C-1, there are a total of three sampler pairs over the free product area; eight pairs on the border of the area, with the remaining seven pairs further away. These locations were chosen to provide a wide variety of soil gas concentrations.

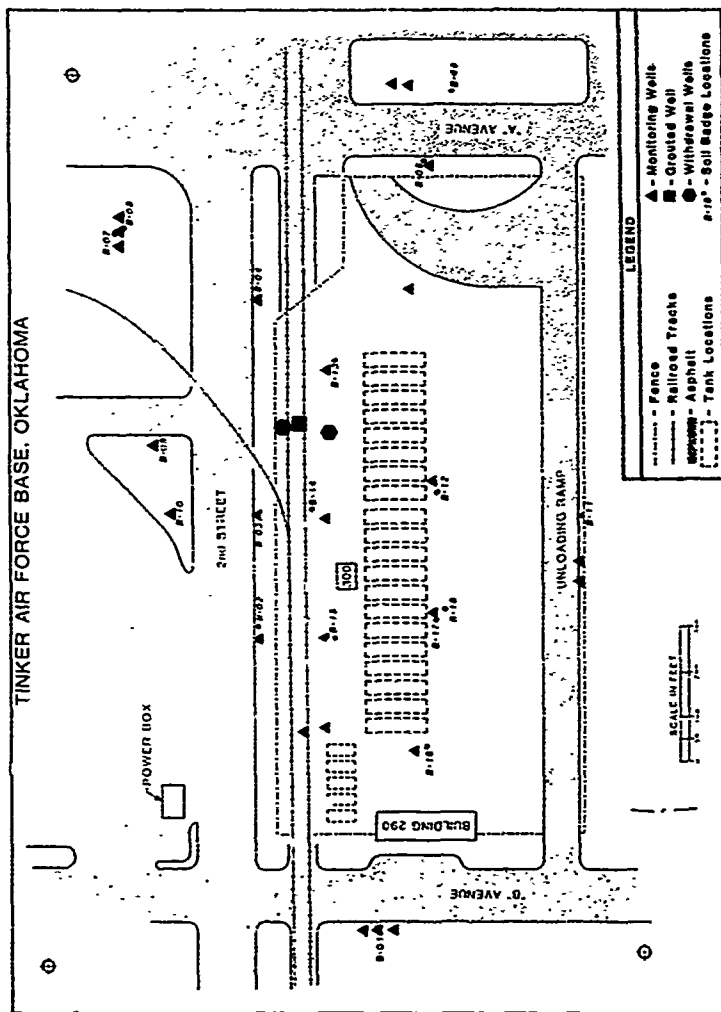
The second soil gas study used an active, real-time technique and was performed during the week of November 11 to November 15, 1986. A total of 30 soil gas samples were collected as is shown in Figure C-3. The soil gas samples were collected from a predetermined depth of 1 to 1.6 meters (3 to 5 feet). This depth was selected due to the perched water table present at depths between 2.1 and 2.6 meters (7 and 8 feet). The optimum sampling depth was unattainable at six locations due to an impermeable clay layer. It was then determined in the field that a sample collected at a depth range of 0.6 to 1 meter (2 to 3 feet) would be considered to provide valid data. These samples were analyzed for benzene, toluene, ethyl benzene, xylene, and total hydrocarbons without methane.

At the same time the second soil gas survey was performed, 13 water samples were collected from the existing monitoring wells as shown in Figures C-2 and C-3. Polyethylene tubing and a peristaltic pump were used; the well was not purged. Measurements of depth to the water table and the thickness of the floating product at the existing monitoring wells made it possible to check the present location of the plume against that as determined by previous studies.

The passive soil gas samplers were installed and removed by EPA and Air Force personnel; the sampler analyses were performed by Lockheed Engineering and Management Services Company, Inc., personnel at EMSL-LV. The active soil-gas sampling effort and the ground water analyses were conducted by Tracer Research Corporation, Inc. under contract to EPA. Water level and floating product measurements were performed by EPA.

#### D. GROUND WATER RESULTS

Maps showing depth to water table and thickness of floating product determined from EMSL-LV measurements are provided in Figures C-4 and C-5. The water table map shows ground water flow direction is to the northeast. The map of thickness of floating product shows thicknesses ranging from 0 to 2.5 meters (8.2 feet). Assuming the wells are screened in the same manner, and the permeability of the soil around each well is similar, then the thickness of floating product will be proportional to the amount of product in the formation. However, the thickness in the well will be greater than the thickness in the formation. These figures show that the greatest thicknesses correspond in location and general extent to the previous results. There has been very little change in plume location since the earlier study was done.



**Figure C-2. Passive Soil Gas Sampling Locations, Fuel Farm 290, Tinker AFB.**



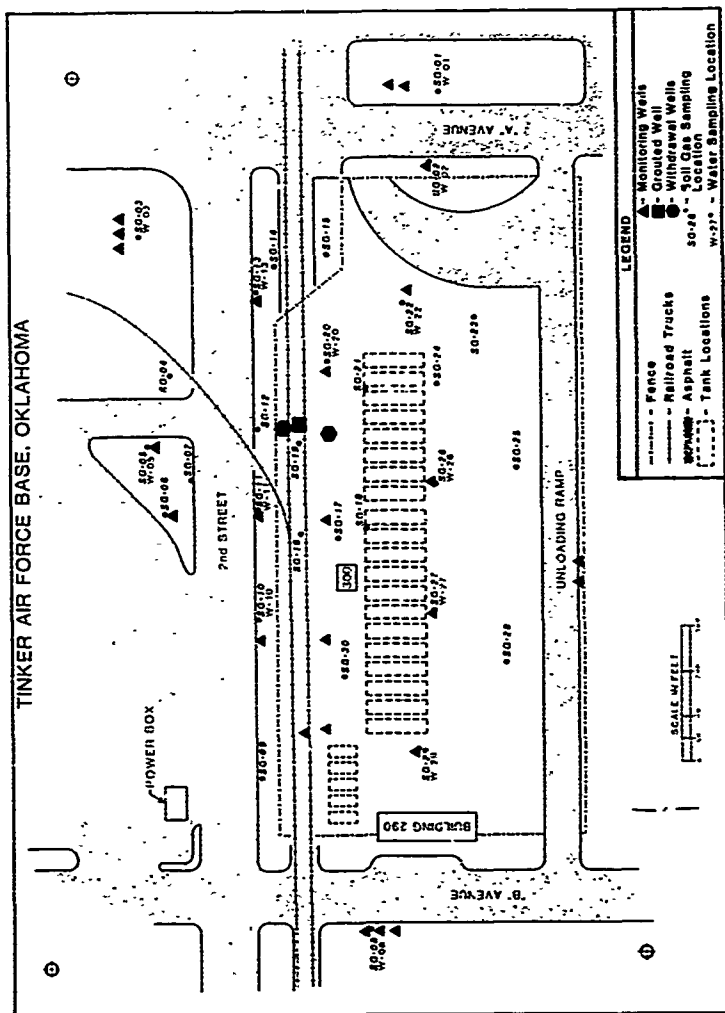


Figure C-3. Active Soil Gas and Ground Water Sampling Locations, Fuel Farm 290, Tinker AFB.

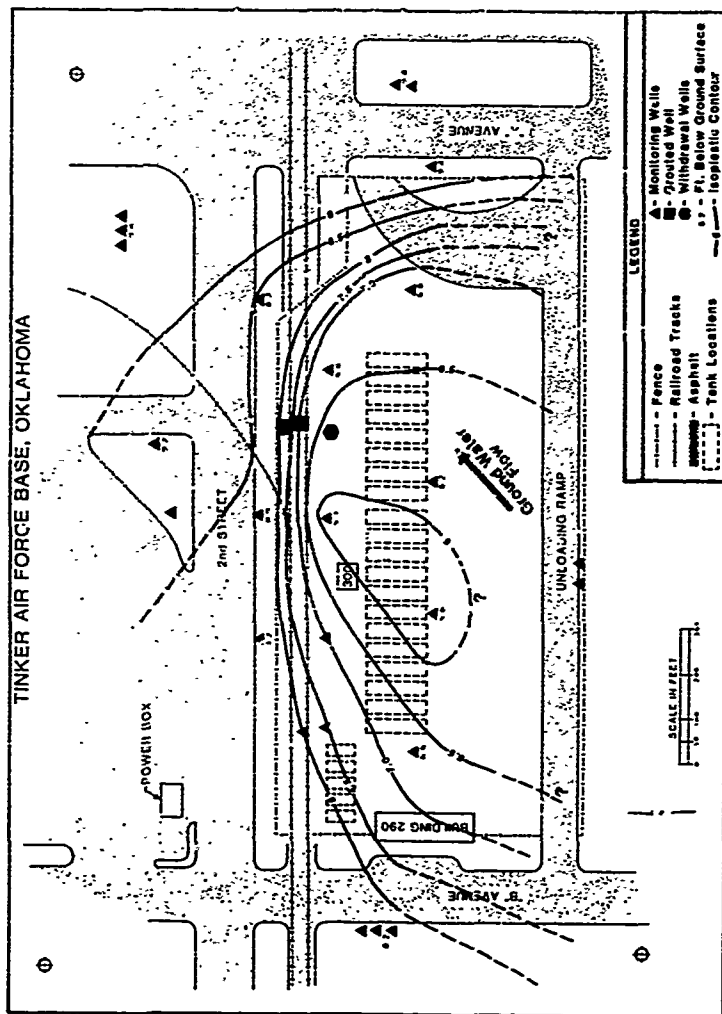


Figure C-4. Depths to Water Table at Fuel Farm 290, Tinker AFB.

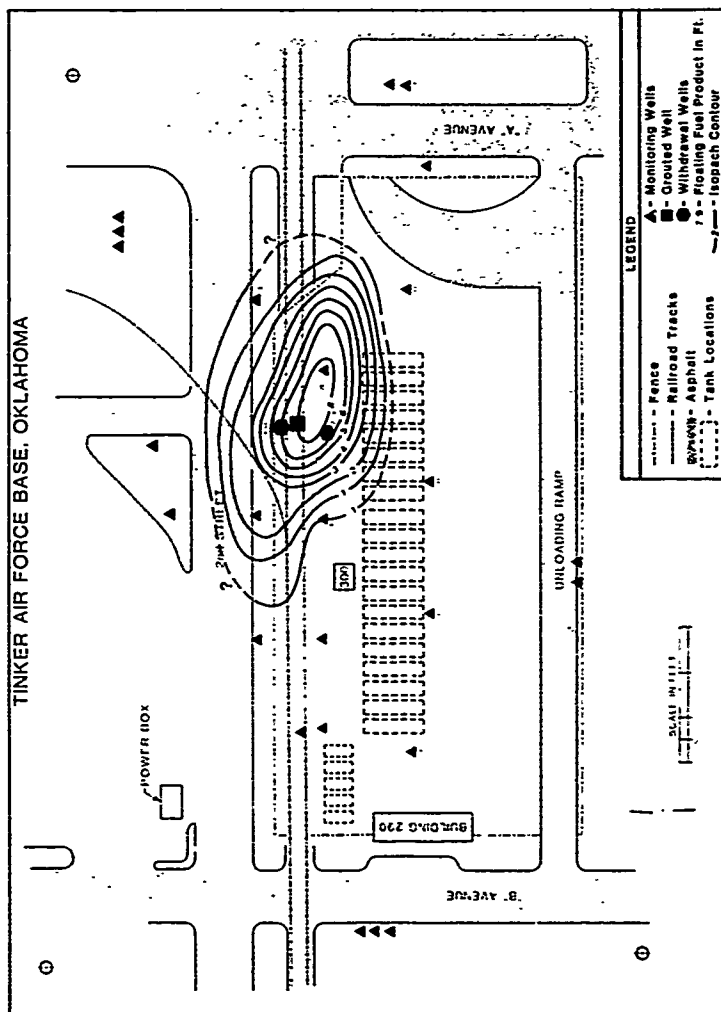


Figure C-5. Thickness of Floating Product at Fuel Farm 290, Tinker AFB.

Maps showing concentrations of benzene, toluene, and total hydrocarbons in ground water are provided in Figures C-6, C-7, and C-8. Values for ethyl benzene and o-xylene were below detectable limits except in three and two cases respectively; maps could not be prepared for these compounds. The maps for benzene, toluene, and total hydrocarbons are very similar to each other and to the floating product map in Figure C-1. These data provide the most direct information on the location of the contamination, and provide the base of information to which the soil gas measurements were compared. In two cases when floating product was present, ground water samples were not collected. The high concentrations present in these samples would have contaminated the GC column, requiring it be heated to a high temperature for several hours before it could be used again, a time-consuming process.

## E. SOIL GAS RESULTS

### 1. Active Soil Gas Sampling

Maps of the active soil gas sampling data for benzene, toluene, and total hydrocarbons are provided in Figures C-9, C-10, and C-11. Maps for ethyl benzene and xylene were not prepared because only four and two values respectively were greater than detection limits. These isoconcentration maps indicate that the subsurface contamination occurred in one major area. This area incorporates the area corresponding to the floating-product as determined by the ground water samples and the floating-product measurements. The highest concentrations of contaminants were located in the northern most section of the fuel farm, forming an east-west elliptical zone between sampling points SG-10 and SG-14. This zone is easily identified in all three isoconcentration maps. However, high values also occurred in the western and southern areas of the Fuel Farm and may be isolated spots around SG28 and SG29. No further conclusions could be drawn for this area because of the limited data available. The contours are drawn to include these points in the high area.

At most locations, the clay soil did not affect the collection of the soil gas sample. Two anomalously low values occur at SG17 and SG20, in the midst of some of the highest values measured. This may be attributed to variability in soil gas concentration and soil permeability, or sampling error. The most likely reason for these low values is the extreme hardness, high clay content and associated low permeability of the soil in this area. In other areas, the soil was more friable. It was not difficult to determine when the soil gas probe was inserted into clay; the vacuum values required to draw a sample increased substantially. It was observed that samples were usually not valid at vacuum pressures greater than 1.36 atmospheres (20 pounds per square inch). It would be desirable to record vacuum values along with the other data, to aid in validation of the results. Overall, in spite of the clay soil, the active soil gas measurements successfully mapped the location of the contaminated ground water.

### 2. Passive Soil Gas Sampling

Maps showing the passive sampling data for total hydrocarbons using data for the nominal 24- and 96-hour exposure times are provided in Figures C-12 and C-13. These concentrations were computed using equation (4) and exposure times for each sampler, nominally 24 and 96 hours. The maps show some similarities in the patterns for the 24- and 96-hour data. However,

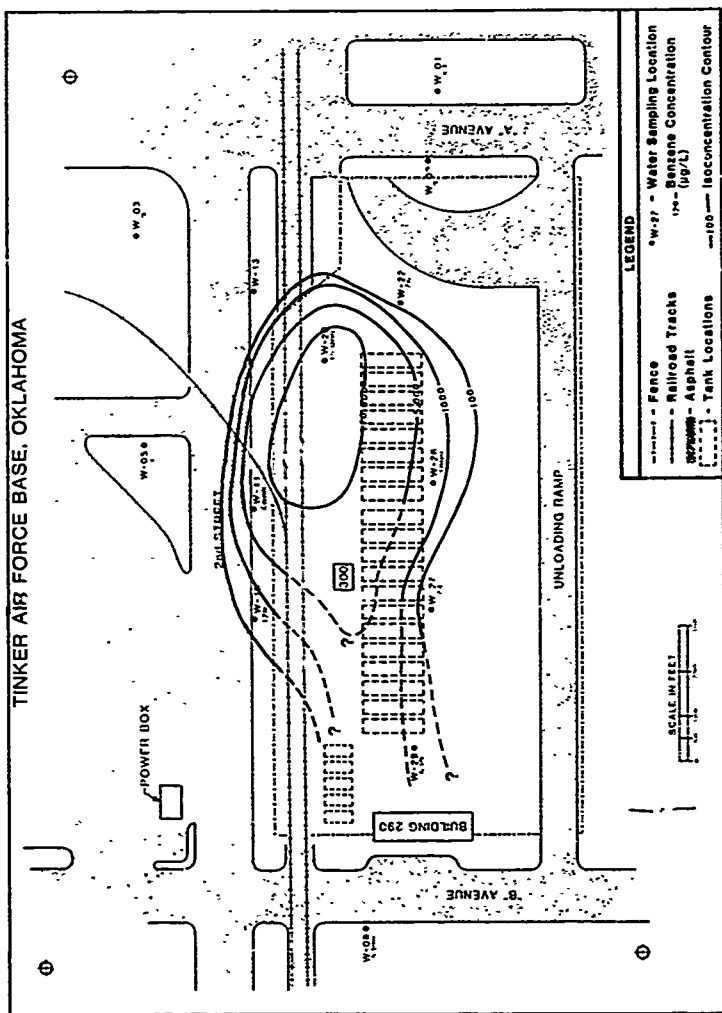


Figure C-6. Concentrations of Benzene in Ground Water at Fuel Farm 290, Tinker AFB.

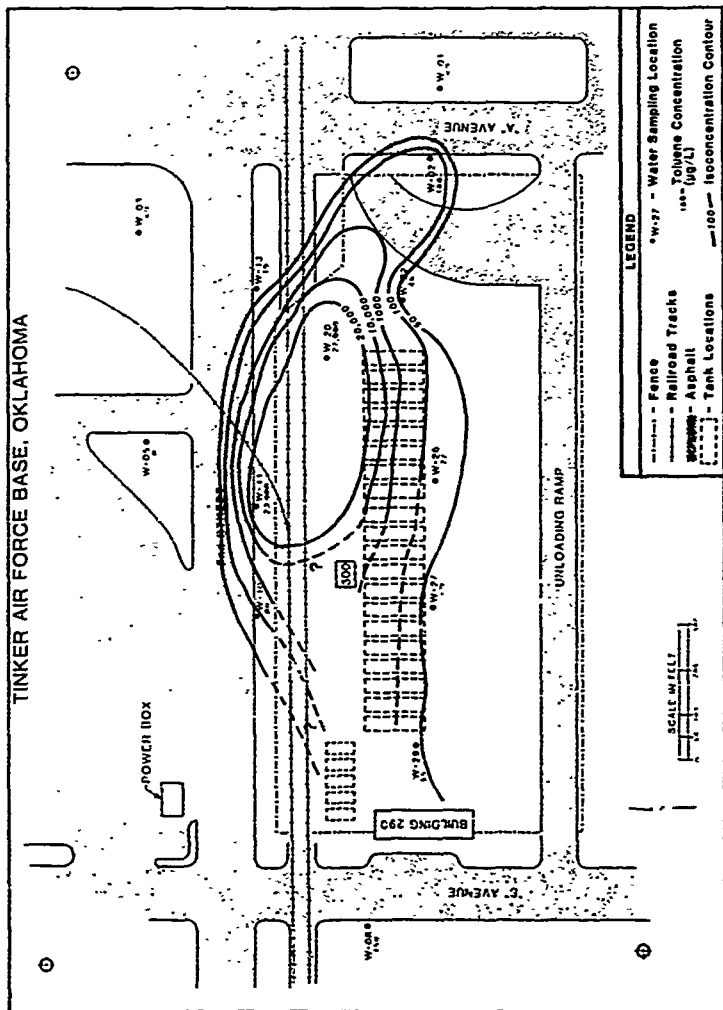


Figure C-7. Concentrations of Toluene in Ground Water at Fuel Farm 290, Tinker AFB.

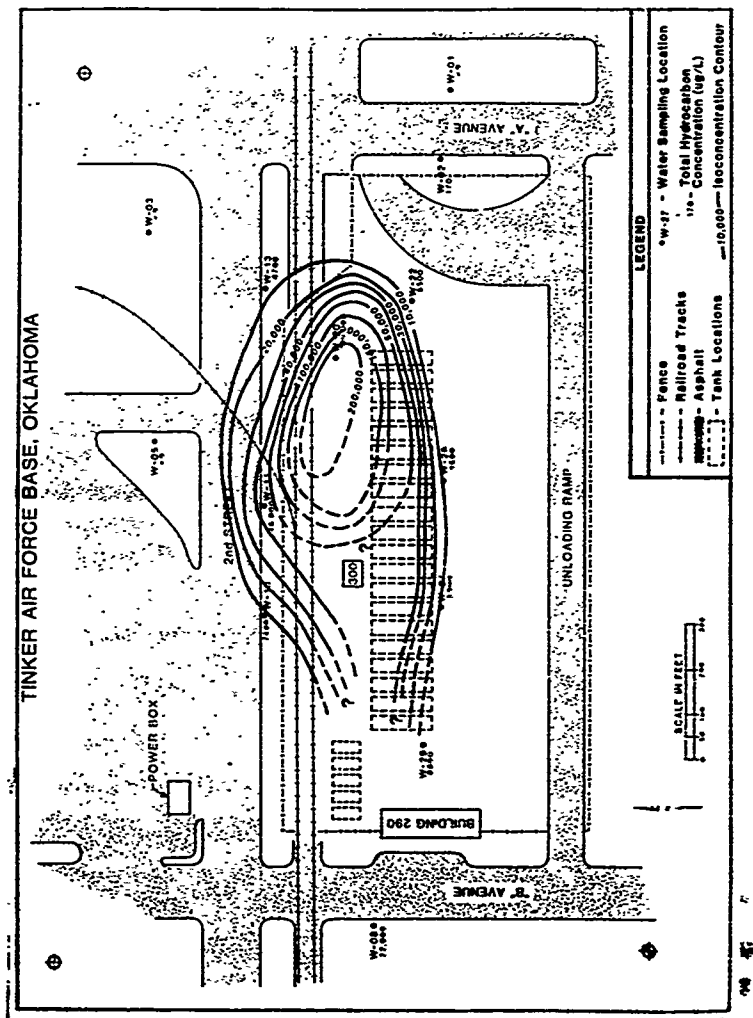


Figure C-8. Concentrations of Total Hydrocarbons in Ground Water at Fuel Farm 290, Tinker AFB.

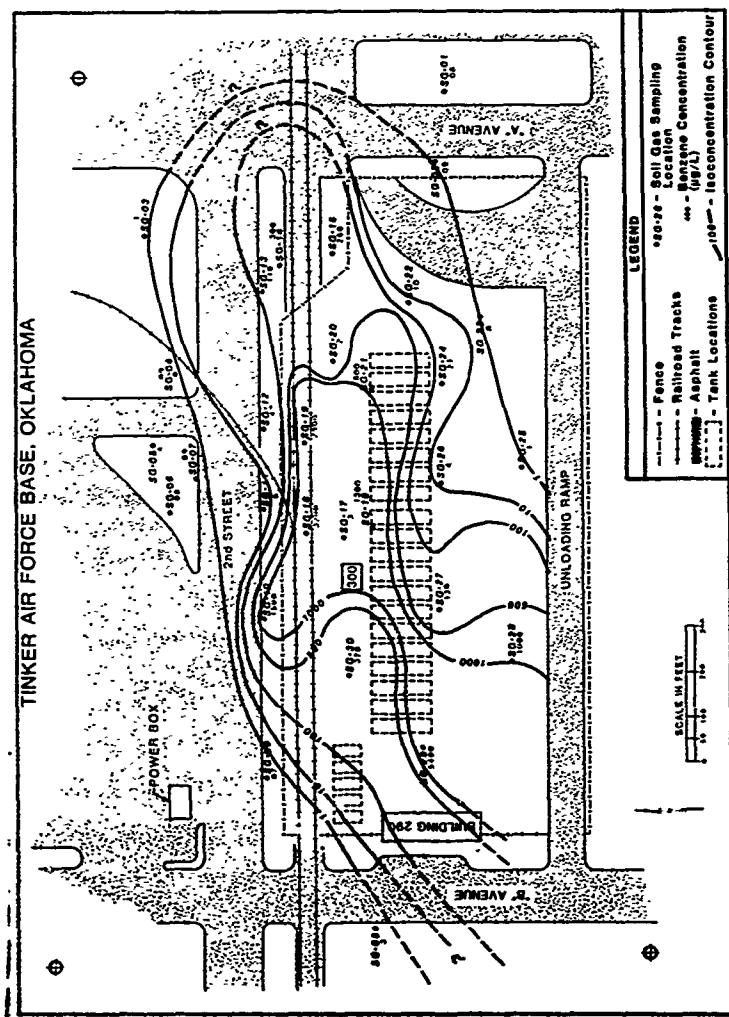


Figure C-9. Active Soil Gas Sampling Results for Benzene at Fuel Farm 290, Tinker AFB.



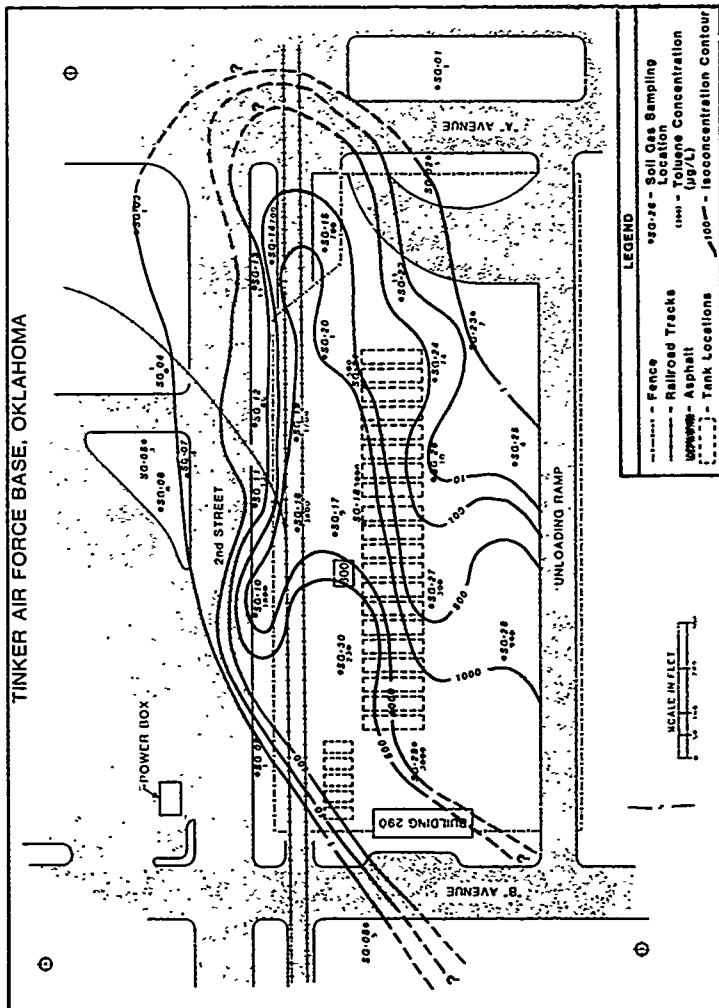


Figure C-10. Active Soil Gas Sampling Results for Toluene at Fuel Farm 290, Tinker AFB.

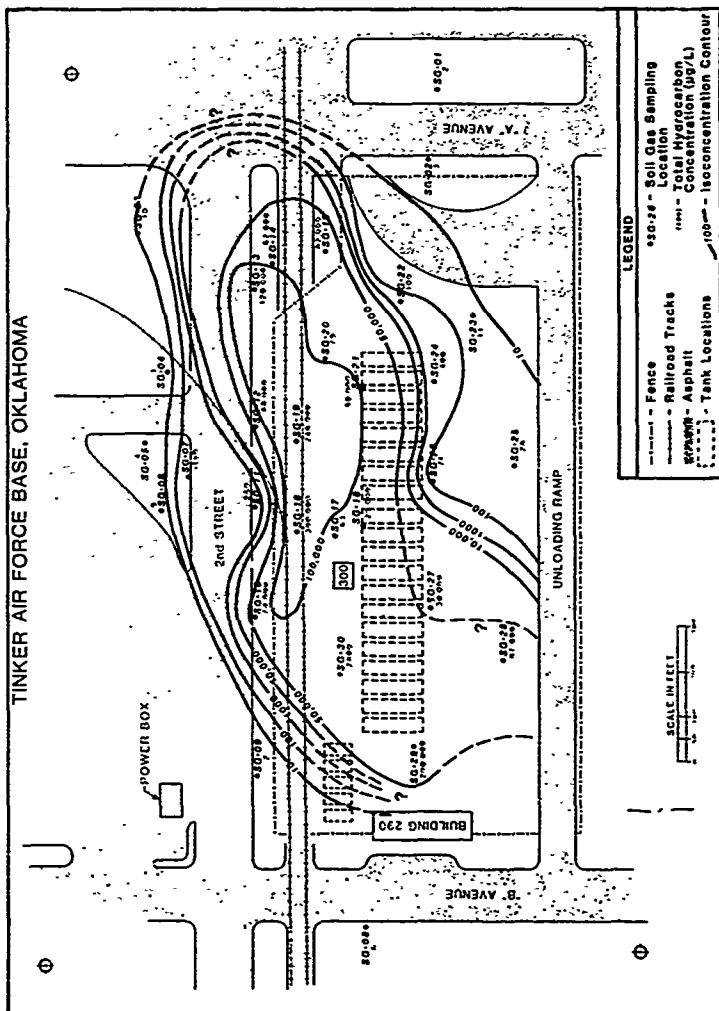
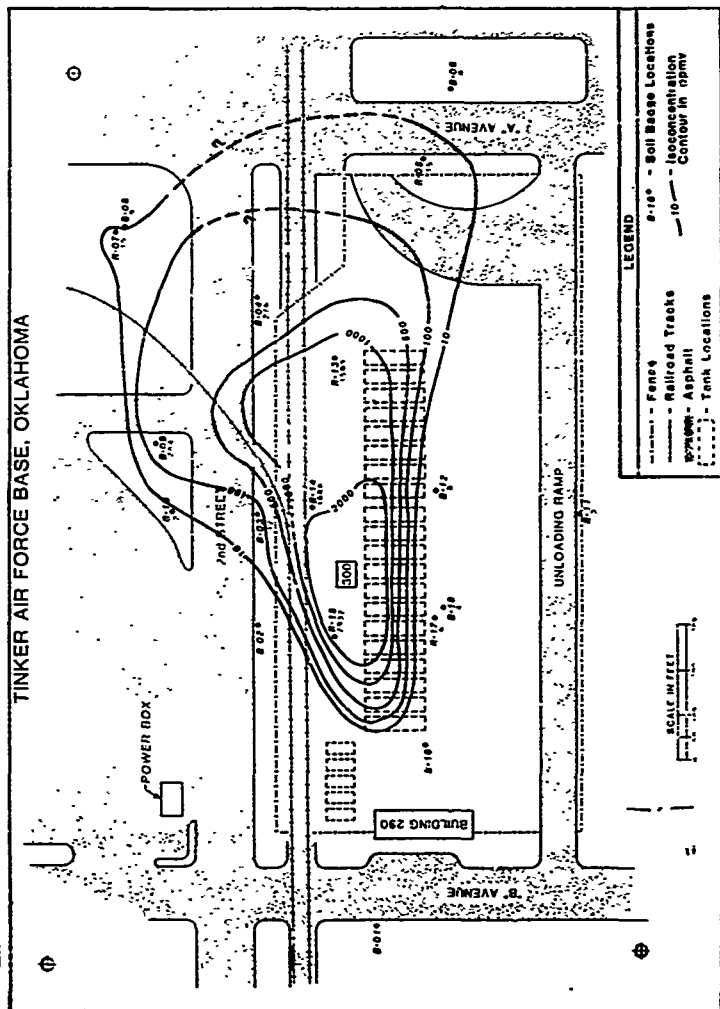
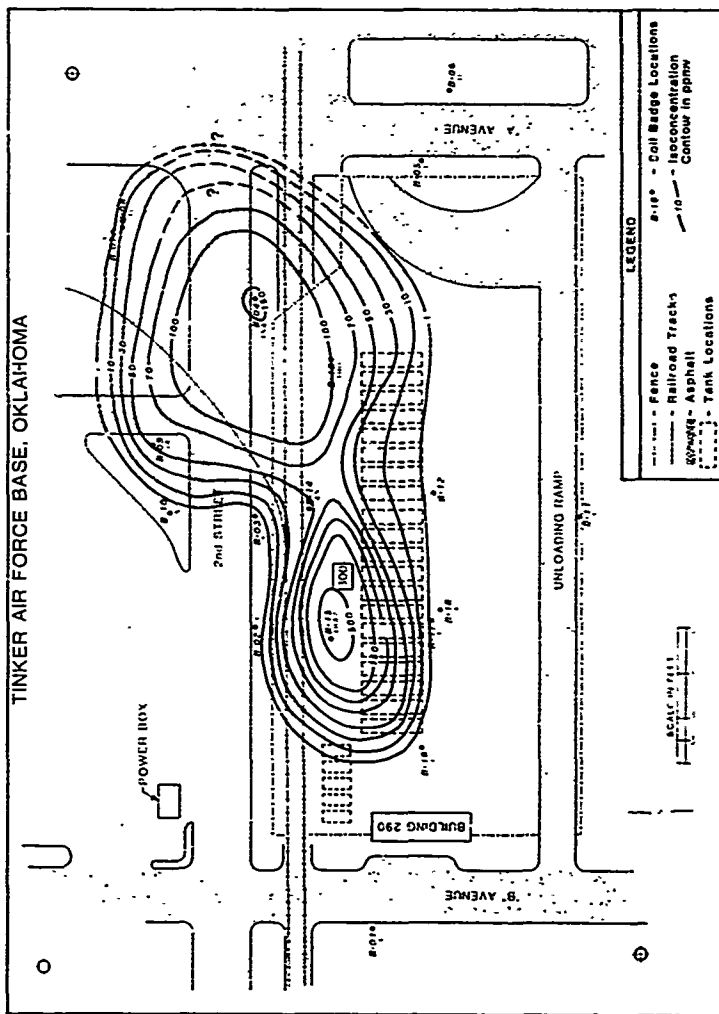


Figure C-11. Active Soil Gas Sampling Results for Total Hydrocarbons at Fuel Farm 290, Tinker AFB.



**Figure C-12. Passive Soil Gas Sampling Results for Total Hydrocarbons with a Nominal 24-Hour Exposure Time at Fuel Farm 290, Tinker AFB.**



concentrations for the 96-hour data were often substantially lower than those for the 24-hour data. In addition, it is interesting to note that while one area of high concentrations at the western end of the tanks is reflected in both sets of data, another area more closely aligned with the floating product location was delineated clearly only in the 96-hour data. In comparing the passive soil gas data with the ground water data, the general features depicted by the passive soil gas data are not the same as the ground water data. This is partly because a number of samples were collected where there was no corresponding data from wells, at the western end of the tanks. A more complete comparison of these data with active soil gas and ground water data appears in the comparisons discussion.

Variability information for this method is provided in Table C-1 including values for the trip blanks and the duplicates. The trip blank values are higher than the values detected in some samples. This suggests that the ambient atmosphere may be contaminated with hydrocarbons, which is reasonable near a fuel farm. The duplicate data show good agreement for the badges installed in the low concentration area, and reasonably good agreement for three out of four of the badges installed in the higher concentration area.

The variations in the duplicate data may be due to local inhomogeneities in contamination or in soil permeability; another possibility is that the well nearby collects the hydrocarbon vapors, reducing the concentrations in the soil. If the well were screened into the vadose zone as might be desired to collect floating product, the well might also collect soil vapor, causing reduced soil gas concentrations in the surrounding soil.

TABLE C-1. VARIABILITY INFORMATION FOR THE PASSIVE SAMPLER TECHNIQUE.

| Total Hydrocarbon Concentration<br>parts per million by volume (ppmv) |                            |                            |
|---|----------------------------|----------------------------|
| Blanks:   |                            |                            |
| Trip Blank 1  |                            | 1.1                        |
| Trip Blank 2  |                            | 2.4                        |
| Duplicates:   | 24-hour<br><u>exposure</u> | 96-hour<br><u>exposure</u> |
| Moderate Concentrations   |                            |                            |
| B-07  | 704.0                      | 5.0                        |
| B-08  | 422.0                      | 460.0                      |
| Low Concentrations  |                            |                            |
| B-17  | 27.0                       | 50.0                       |
| B-18  | 18.0                       | 18.0                       |

A troubling issue is the large differences in values for the nominal 24- and 96-hour exposure times. The passive sampler data are listed in order from lowest to highest in Table C-2. For example, the highest values detected for this method are 2931 parts per million, volume (ppmv) at B-30; 1688 ppmv at B-16; and 1510 ppmv at B-20, for the 24-hour exposure time. The corresponding data for these locations for 96-hour exposure times are 1047 ppmv at B-30; 44.7 ppmv at B-16, and 100 ppmv at B-20. This same pattern shows for samples at lower concentrations. It was expected that badge loadings for the longer time would be greater than for the shorter time. In this case, it was generally not true. In another study performed in an area with mixed sand and gravel soil, badge loadings for long-term exposures were greater than those for short term exposures (Reference 10). Reasons for the differences may include natural and man made variability in the soil from location to location; variations in the soil gas concentrations resulting from changes in barometric pressure, soil moisture, temperature, or relative humidity during the latter days of the 96-hour sampling period; saturation of the badges by organic or water vapor; decreased collection efficiency due to increased humidity; or limitations in the diffusion rate of VOCs through the surrounding soil. These possibilities are discussed further below. It is also possible that a sampling volume established for industrial hygiene purposes may not be appropriate for a badge sampling from soil. This is a topic for further investigation.

TABLE C-2. PASSIVE SOIL GAS DATA FROM BADGES SORTED  
FROM LOWEST TO HIGHEST

| Concentration (ppmv) |         |               |
|----------------------|---------|---------------|
| 24-hour              | 96-hour | Sample number |
| invalid data         | 0.1     | B-01          |
| invalid data         | 0.1     | B-02          |
| 0.4                  | 0.1     | B-18          |
| 0.6                  | 1.0     | B-17          |
| 0.8                  | 0.0     | B-06          |
| 0.8                  | 0.2     | B-12          |
| 1.4                  | 0.1     | B-16          |
| 1.5                  | 0.4     | B-10          |
| 3.0                  | 0.1     | B-11          |
| 8.7                  | 9.5     | B-08          |
| 12.3                 | 0.1     | B-03          |
| 14.5                 | 0.1     | B-07          |
| 15.3                 | 0.3     | B-05          |
| 276.5                | 153.9   | B-04          |
| 284.1                | 54.0    | B-09          |
| 1509.5               | 100.3   | B-13          |
| 1688.3               | 44.7    | B-14          |
| 2931.8               | 1046.9  | B-15          |

Since the samplers in each pair were placed as much as 2 meters (6 feet) apart, it is conceivable that the badges installed for the 96-hour exposure period were somehow installed in locations with lower soil gas concentrations. However, the data for duplicates shows that for those cases, the order-of-magnitude variations cannot be explained by the installation pattern used.

The possibility of changes in soil gas concentration due to changes in barometric pressure, temperature, and humidity in soil gases during the exposure period was considered. These parameters were not measured, so no evaluation is possible. Saturation of the badges is unlikely because of the capacity of the badges.

The possibility of a decrease in sampler efficiency due to increased humidity was considered. However, because the pattern observed applies to both high and low concentrations, decreased efficiency could not be the factor. For example, increased humidity would decrease the sampler capacity for VOCs, and the effect would be observed only for higher concentrations.

The possibility that the amount of VOCs moving to the badge was being limited by the diffusion rate was also considered. In this concept, the badge would adsorb the soil gas in the soil pores near the badge. Additional adsorption would depend on the diffusion of additional vapors to the collection area. If the diffusion rate was very slow compared to the adsorption rate of the badge, then the badge would only be able to sample from a fixed volume near the badge. Vapor diffusion is known to be slow in clay. However, without additional information, this possibility cannot be evaluated further.

To summarize, the badge data delineated two contaminated areas, one confirmed by the ground water data, and one in an area with limited ground water data. The duplicate data generally showed good agreement, and the pattern in concentrations observed may be due to the location of individual samplers in relation to the well and ground water flow direction. A surprising result was that the loadings on badges exposed for 96 hours were approximately the same as the loadings on badges exposed for 24 hours. A possible explanation for this phenomena is that the movement of soil vapors to the badges is diffusion limited for this clay soil. A number of other possibilities were also considered; the necessary information was not available to evaluate them.

### 3. Comparisons

As shown in Figures C-2 and C-3, the study was planned so that ground water samples and passive and active soil gas samples each would be collected within 1 meter (3 feet) of the monitoring wells at 12 locations. These locations span all areas of contamination, from the most contaminated to the least. To further compare the results from the different methods, the data were displayed using three circles placed next to the wells where multiple techniques were used. The top, northern most circle corresponds to active soil gas results; the middle circle corresponds to ground water data; and the bottom, southern most circle corresponds to the passive soil gas data. The circle was darkened if the value reported for that technique exceeded a criterion. For Figure C-14, which is a comparison of high values measured by each technique, the criterion was that a value must exceed the lowest background value for that technique by at least a factor of 100. For Figure C-15, a medium and high value comparison, a value had to be greater than the background values for that technique. All circles darkened or all empty indicates all three techniques agree. This occurs at four locations in both cases. The sample from the western most set of wells shows a high ground water concentration, but low active and passive soil gas concentrations. This well is believed to be screened at a different depth than the other wells, and not indicative of the same contamination.

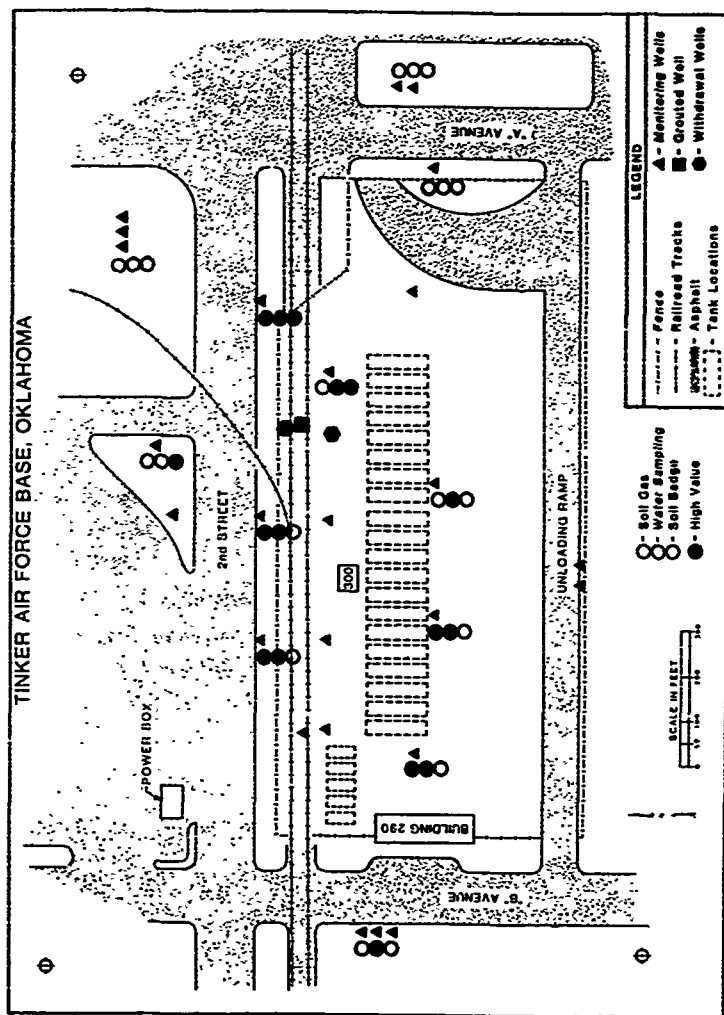


Figure C-14. Comparison of High Values Measured by Each Technique at Fuel Farm 290, Tinker AFB.



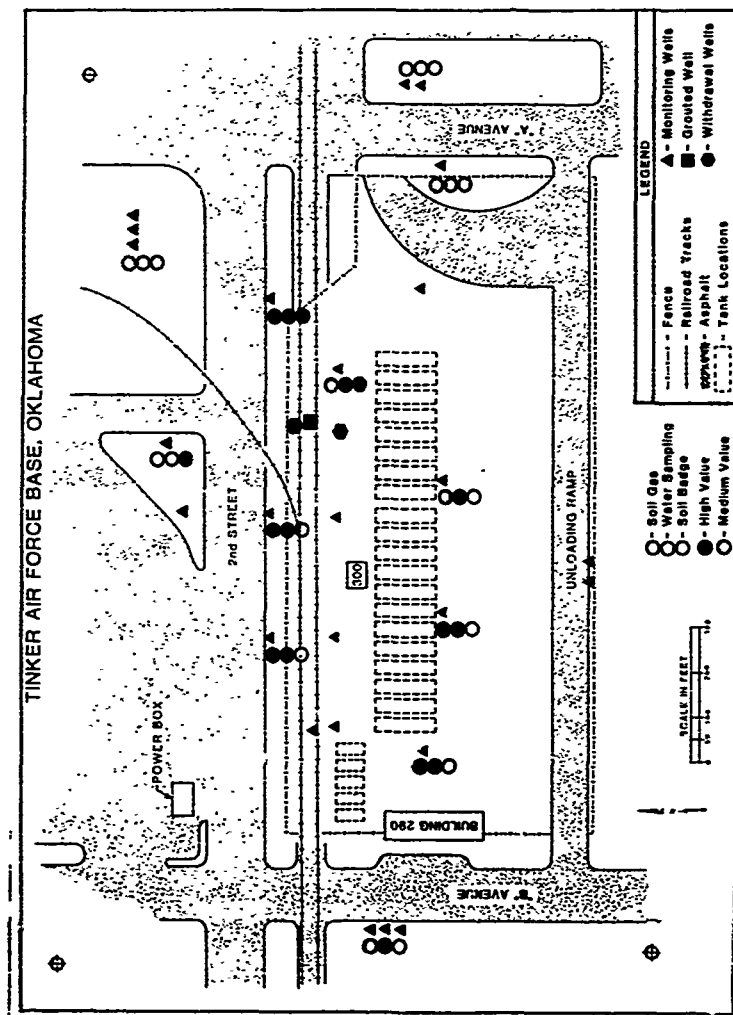


Figure C-15. Comparison of Medium and High Values Measured by Each Technique at Fuel Farm 290, Tinker AFB.

Active soil gas and ground water results agree at 9 locations in the comparison of high values, and at 10 locations in the comparison of medium and high values. Passive soil gas and ground water data agreed at 5 locations in the high values comparison, and at 5 locations in the medium and high values comparison. The active soil gas technique did not detect the contamination indicated by the ground water samples at 3 locations in the high value comparison and 2 locations in the medium and high value comparison.

The passive soil gas data agreed less frequently with the ground water data than the active soil gas data. This suggests that the badge soil gas technique may not be responding to the same contamination as the active technique. One reason this may occur is the differing depths of sampling; the soil gas samples were collected at depths of 0.6 to 1.1 meters (2 to 4 feet) while the passive samplers were installed at a depth of 0.3 meters (1 foot). Being nearer to the surface would make the badges more sensitive to surface contamination, and to the effects of degradation. This suggests that for the two soil gas measurement techniques to be comparable, a method must be developed to install the passive samplers at depths similar to those used in active soil gas sampling. Of course, there will be cases such as delineating surface contamination, when the shallow sampling depth is an advantage.

#### F. SUMMARY

To summarize, the active soil gas data compared favorably with the ground water data in spite of the clay soil. When working in clay, it would be desirable to record vacuum values along with the other data, to aid in validation of the results. At this site, high vacuum values were indicative of an invalid sample. Overall, the active soil gas measurements successfully mapped the location of the contaminated ground water.

The passive soil gas data agreed less frequently with the ground water data than the active soil gas method. This suggests that the passive soil gas technique may not be responding to the same contamination as the active technique. One reason this may have occurred is the differing depths of sampling. Being nearer to the surface would make the badges more sensitive to surface spills, and to the effects of degradation. This suggests that for the two soil gas measurement techniques to be comparable, a method must be developed to install the passive samplers at depths similar to the active sampling depths. Further testing of the performance of this technique is recommended before it is used routinely. Because of its low cost, this passive soil gas sampling has potential for reducing site investigation costs, if some of the questions about the technique can be resolved.